the residential area, local street traffic and other community activities could dominate the ambient noise. In this example, three or more measurement sites would be required to represent the varying ambient noise conditions in a single neighborhood.

Representative measurement sites typically can be used to estimate noise levels at other sites when both share the following characteristics:

- proximity to the same major transportation noise sources, such as highways, rail lines, and aircraft flight patterns,
- proximity to the same major stationary noise sources, such as power plants, industrial facilities, rail yards and airports, and
- similar type and density of housing, such as single-family homes on quarter-acre lots and multi-family housing in apartment complexes.

Acoustical professionals are often adept at such computations from partial data and are encouraged to use their experience and judgement in fully utilizing the measurements in their computations. On the other hand, people lacking a background in acoustics should use the procedures in Appendix B to accomplish this same aim. The procedures contained in Appendix B are an attempt to systematize such computations from partial measurements. As a safety factor, these procedures underestimate ambient noise to account for reduced precision compared with full noise measurements.

5.2 PROJECTIONS OF HIGH-SPEED RAIL NOISE

Once receivers have been selected, projections of noise from high-speed trains can be developed for each receiver. The subsequent steps in the computation procedure, described in detail in Sections 5.2.1 through 5.2.5, are:

Step 3. **Source Reference Levels**. Establish the type of system for the proposed high-speed rail project. Determine the reference SEL, length, and speed relationship for each noise subsource on the train.

Step 4. **Project Operating Conditions**. Adjust each subsource SEL to the operating conditions of the project (consist and speed).

Step 5. **Propagation of Noise to Receivers**. Estimate the propagation effects of geometric spreading, ground attenuation, and shielding for each subsource SEL to develop an SEL-versus-distance relationship. Compute an overall, combined SEL from all subsources for a single train passby as a function of distance.

Step 6. **Total Noise Exposure**. Use the project's operating parameters to calculate overall noise exposure at each receiver from the combined SEL.

Step 7. **Maximum Noise Level for Train Passbys**. If necessary, calculate the maximum noise Level (L_{max}) from a single train passby. L_{max} is not used in the assessment of noise impact, but may be useful for comparisons with measurement data or project specifications.

5.2.1 Step 3: Source Reference Levels

The wayside noise level generated by a high-speed train passby depends primarily on system design and its operating conditions. The SEL used to describe a given system under a fixed set of operating conditions (speed, consist, track configuration) at a reference distance is called the **source reference level.** Since a number of high-speed rail systems are in existence worldwide, with design variations ranging from the type of propulsion mechanism to the car body shape, it is necessary to develop a set of generalized source reference levels for use in the prediction model established in this manual. A review of available data resulted in grouping all existing high-speed rail systems into the following five categories:

- ***High-Speed, Steel-Wheeled Electric***
  Electric-powered, locomotive-hauled trains with maximum operating speeds of 125 to 150 mph,

- ***High-Speed, Steel-Wheeled Fossil Fuel***
  Fossil fuel-powered, locomotive-hauled trains with maximum operating speeds of 125 to 150 mph,

- ***High-Speed, Steel-Wheeled EMU***
  Electric-powered multiple unit (EMU) trains with maximum operating speeds of 125 to 150 mph,

- ***Very High-Speed, Steel-Wheeled Electric***
  Electric-powered, locomotive-hauled trains with maximum operating speed of 200 to 250 mph, and

- ***Maglev***
  Magnetically-levitated trains with maximum operating speed of 250 mph and up.

Once the appropriate system category is selected, the first action in the detailed noise prediction procedure for high-speed train passbys is to establish the source reference level and the corresponding reference conditions for that category. Depending on the system category, this source reference level can be broken down into two or more *subsources* as described in Chapter 2. These subsources relate directly to the various location-specific noise-generating mechanisms on the train, and can be categorized into one of the following three component categories:

- propulsion,
- mechanical, or
- aerodynamic noise.

The relevant subsources and their nominal noise reference levels to be used in computing noise exposure for each of the five system categories are listed in Table 5-2. In this table, the reference SEL for each subsource is given for the reference distance of 50 feet from the track centerline. Also given in the table are the definition and reference value of the associated length of each subsource; for example, wheel-rail noise is associated with the entire train length, while propulsion noise originates only from the power cars. The subsource length is an important parameter, since SEL is an energy descriptor and for a train is always defined normalized to some reference length. The subsource heights, expressed in terms of the height above the rails (or guideway), are also listed in Table 5-2 and are used in evaluating shielding and other propagation effects as described in Section 5.2.3.

The levels in Table 5-2 are based on the results of the background measurement and research program that preceded the preparation of this manual. That program has resulted in an extensive database of noise data on most existing high-speed rail systems, ensuring that Table 5-2 is reasonably accurate for the existing technologies. However, when specific equipment has been selected for a project, it will be more accurate to base the impact assessment on noise measurements of that equipment.[3]

For some projects, source-noise levels will be pre-defined; for example, noise limits are usually included in the specifications for purchase of new vehicles. Compliance with such specifications, almost always defined in terms of L_{max}, can be checked using the equations found in Appendix C. This option is addressed further in Section 5.2.5, accompanied by an example in which noise projections are used to determine compliance with a noise specification given in terms of L_{max}.

[3]As a cautionary note, measurements to obtain reference quantities as in Table 5-2 require special techniques to separate subsource components and are beyond the scope of this manual. If single level measurements are performed, methods for converting these levels to the simplified reference levels used in the General Assessment procedure (Chapter 4) are given in Appendix C.

Table 5-2 **Source Reference SELs at 50 feet**

System Category and Features [a]	Example Systems	Subsource Component		Subsource Parameters: Length Definition, *len*	Subsource Parameters: Height above rails (ft)	Reference Quantities: SEL_{ref} (dBA)	Reference Quantities: len_{ref} (ft)	Reference Quantities: S_{ref} (mph)	Reference Quantities: *K*
HS ELECTRIC • ***Steel-Wheeled*** • ***High-Speed*** • ***Locomotive-Hauled*** • ***Electric Power***	X2000 Talgo (electric) Amtrak HST	Propulsion		len_{power}	10	86	73	20	15
		Wheel-rail		len_{train}	1	91	634	90	20
HS FOSSIL FUEL • ***Steel-Wheeled*** • ***High-Speed*** • ***Locomotive-Hauled*** • ***Fossil Fuel Power***	RTL-2 Talgo (gas turbine)	Propulsion		len_{power}	10	83	73	20	10
		Wheel-rail		len_{train}	1	91	634	90	20
HS EMU • ***Steel-Wheeled*** • ***High-Speed*** • ***Electric Multiple Units (EMU)***	Pendolino IC-T	Propulsion		len_{power}	10	86	73	20	1
		Wheel-rail		len_{train}	1	91	634	90	20
VHS ELECTRIC • ***Steel-Wheeled*** • ***Very High-Speed*** • ***Locomotive-Hauled*** • ***Electric Power***	TGV Eurostar ICE Shinkansen	Propulsion		len_{power}	12	86	73	20	0
		Wheel-rail		len_{train}	1	91	634	90	20
		AERO	Train Nose	len_{power}	10	89	73	180	60
		AERO	Wheel Region	len_{train}	5	89	634	180	60
		AERO	Pantograph	[b]	15	86	–	180	60
MAGLEV	TR07	Propulsion		len_{train}	0	72	82	20	3
		Guideway/Structural		len_{train}	-5	73	82	60	17
		AERO	Train Nose	len_{power}	5	78	20	120	50
		AERO	TBL [c]	len_{train}	10	78	82	120	50

[a] ***HS*** *(High-Speed)* = maximum speed 125-150 mph
VHS *(Very High-Speed)* = maximum speed 200-250 mph
MAGLEV = maximum speed 250 mph and up

[b] originates as a point source (no length)

[c] Turbulent Boundary Layer

5.2.2 Step 4: Project Operating Conditions

Since the source reference levels given in Table 5-2 are for a specific train length and speed, they must be normalized to reflect the actual operating conditions of the project. In other words, trains whose consists are different from the reference consists assumed in Table 5-2 require conversion since they will produce different noise exposure. The same is true for trains at speeds other than those listed in Table 5-2. As guidance, a 40 percent change in the number of power cars or coaches per train, *or* a 15 percent change in train speed, will produce an approximate 2-decibel change in noise exposure.

Once the appropriate system category and reference quantities are established, the following input parameters are required to adjust each reference SEL to the appropriate operating conditions:

- number of passenger cars in the train, N_{cars},
- number of power units in the train, N_{power},
- length of one passenger car, $ulen_{car}$,
- length of one power unit, $ulen_{power}$, and
- train speed in miles per hour, S.

The following equation should be used to adjust each "*n*th " subsource SEL to the operating conditions identified above:

$$SEL_n = (SEL_{ref})_n + 10\log\left(\frac{len}{len_{ref}}\right)_n + K\log\left(\frac{S}{S_{ref}}\right)_n$$

The consist adjustment in the above equation is reflected in the "10 log(len/len_{ref})" term, where *len* represents the subsource length (len_{power}, len_{train}) specified in Table 5-2. These variables are defined as:

$$len_{power} = N_{power} \times ulen_{power}, \text{ and}$$

$$len_{train} = (N_{power} \times ulen_{power}) + (N_{cars} \times ulen_{car}).$$

The speed adjustment is given by the "K log(S/S_{ref})" term, using the appropriate value for K in Table 5-2.

5.2.3 Step 5: Propagation of Noise to Receivers

Propagation characteristics must now be considered in order to compute the noise exposure at specific receivers, using the project SEL at 50 feet for each subsource as the basis for calculation. The sequence in this process are as follows:

- Determine the propagation characteristics between each subsource and the receiver.
- Develop an SEL-distance relationship for each subsource.
- Add a final adjustment using the appropriate shielding term based on intervening barriers and/or terrain features between subsource and receiver.

The steps required to carry out this sequence, resulting in calculation of a specific noise exposure-versus-distance relationship for each noise subsource, are described below:

1. Set up cross-sectional geometries: Draw several approximate topographic sections, each perpendicular to the path of moving sources or radially outward from point sources, similar to those shown in Figure 5-3. Draw separate sections, if necessary, to account for significant changes in topography and/or track geometry. Use judgement to reasonably limit the number of cross sections required. Fewer than ten "typical" sections throughout the project corridor will usually suffice.

2. Estimate Ground Effects:[4] For each topographic cross section, use the relationships illustrated in Figure 5-3 to determine the **effective path height, H_{eff}**, and from it the **ground factor, G, for the wheel-rail and propulsion noise subsources only**. For aerodynamic noise subsources, ground absorption has little attenuating effect and can be disregarded.

   Larger values of G mean larger amounts of ground attenuation with increasing distance from the source. As shown in Figure 5-3, H_{eff} depends upon subsource heights, which are defined in terms of height above rails in Table 5-2, and upon receiver heights, which is usually taken as 5 feet above ground for both outdoor receivers and first floor receivers.

   Because of the different effective source heights for the wheel-rail and propulsion noise subsources, each will have a different H_{eff} and therefore ground factor. For acoustically "hard" (i.e., nonabsorptive) ground conditions, and for all aerodynamic noise subsources, G should be taken to be zero. Application of the computations in Figure 5-3 is restricted to topographies for which horizontal distances are much greater than the vertical distances. In cases where the vertical distance, such as the elevation of the source or receiver, is of the same order of magnitude as any of the horizontal distances, G can be taken as zero if the line of sight is unbroken. Otherwise use the shielding method described in the next step.

3. Estimate Shielding due to Terrain and Noise Barriers: If the line of sight between subsource and receiver is unbroken, calculation of the ground factor (G) alone is sufficient to describe the attenuation of noise with increasing distance. However, if shielding between source and receiver in the form of intervening noise barriers and/or terrain features due to natural topography or to track geometry (e.g., track in cut or on embankment) breaks the line of sight, an additional attenuation must be included in the calculation of propagation effects.

   Equations for computing the attenuation due to shielding ($A_{shielding}$) are provided in Table 5-3 for the basic cross-sectional geometry shown in the figure at the bottom of the table. This fundamental source-barrier-receiver geometry can also be used to model the barrier effect of terrain features that protrude above the line of sight, such as the edge of a deep cut, an embankment, or an earth berm. Examples of application of the shielding model are shown in Figure 5-4.

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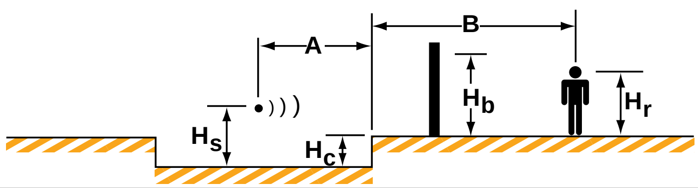
[4]Ontario Ministry of Environment, "ORNAMENT: Ontario Road Noise Analysis Method for Environment and Transportation," November 1988.

IN GENERAL: H_{eff} = sum of average path heights on either side of barrier

$$H_{eff} = \frac{H_s + 2H_b + H_r}{2} \qquad (1)$$

Example 1: Source in shallow cut

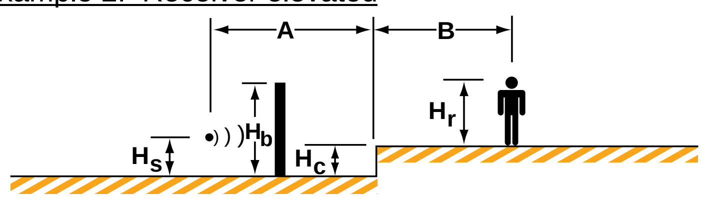


For $B < A/2$,

$$H_{eff} = \frac{H_s + 2H_b + H_c + H_r}{2}$$

* Otherwise use Equation (1)

Example 2: Receiver elevated



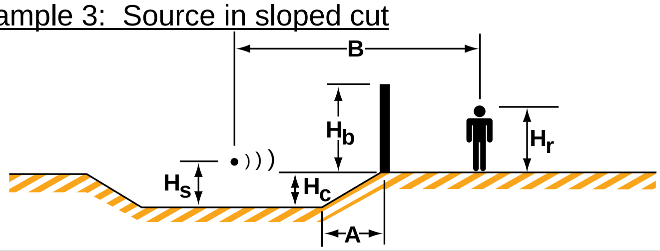
For $H_b > H_c$,

$$H_{eff} = \frac{H_s + 2H_b - H_c + H_r}{2}$$

For $H_b < H_c$,

$$H_{eff} = \frac{H_s + H_c + H_r}{2}$$

Example 3: Source in sloped cut

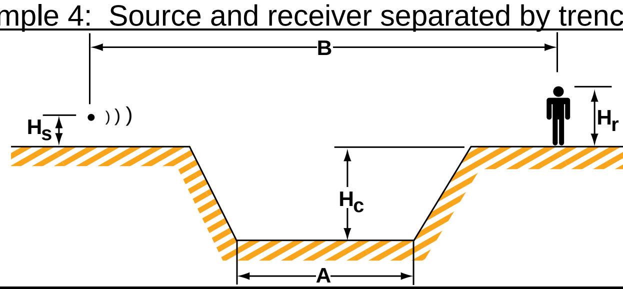


For $A < B/2$,
use Equation (1)

For $A > B/2$,

$$H_{eff} = \frac{H_s + 2H_b + H_c + H_r}{2}$$

Example 4: Source and receiver separated by trench



For $A > B/2$,

$$H_{eff} = \frac{H_s + 2H_c + H_r}{2}$$

For $A < B/2$,

$$H_{eff} = \frac{H_s + H_r}{2}$$

Ground Factor

For soft ground:

$$G = \begin{cases} 0.66 & H_{eff} < 5 \\ 0.75\left(1 - \frac{H_{eff}}{42}\right) & 5 < H_{eff} < 42 \\ 0 & H_{eff} > 42 \end{cases}$$

For hard ground:

$$G = 0$$

Notes:

- Values for Sub-Source Heights (H_s) are given in Table 5-2.
- Equations for H_{eff} remain valid even when H_b=0.

Figure 5-3 Computation of Ground Factor G for Ground Attenuation

Table 5-3 Computation of Shielding: Barriers and Terrain

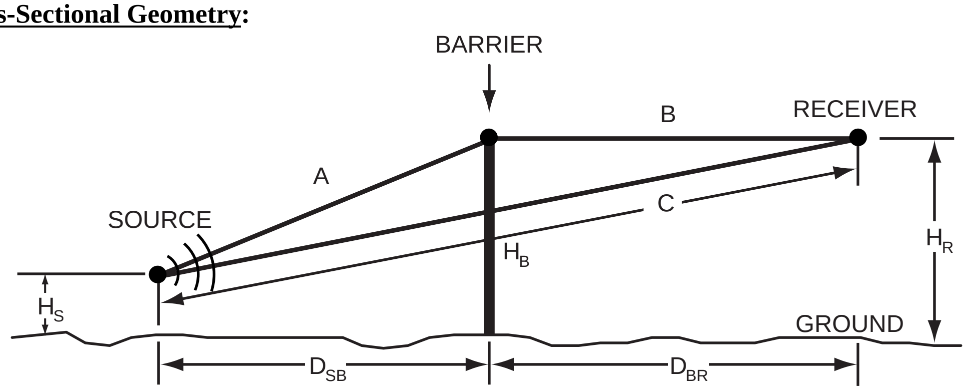
Subsource Type	Equation for Barrier Attenuation
PROPULSION	$A_{barrier} = \min\left\{15 \text{ or } \left[20\log\left(\frac{2.51\sqrt{P}}{\tanh\left[4.46\sqrt{P}\right]}\right)+5\right]\right\}$
WHEEL-RAIL	$A_{barrier} = \min\left\{20 \text{ or } \left[20\log\left(\frac{3.54\sqrt{P}}{\tanh\left[6.27\sqrt{P}\right]}\right)+5\right]\right\}$
AERODYNAMIC	$A_{barrier} = \min\left\{15 \text{ or } \left[20\log\left(\frac{1.25\sqrt{P}}{\tanh\left[2.22\sqrt{P}\right]}\right)+5\right]\right\}$

Barrier Insertion Loss:

$$A_{shielding} = IL_{barrier} = A_{barrier} - 10\left(G_{NB} - G_B\right)\log\left(\frac{D}{50}\right)$$

D = closest distance between the receiver and the source, in feet
P = path length difference, in feet (see figure below)
G_{NB} = Ground factor G computed *without barrier* (see Figure 5-3)
G_B = Ground factor G computed *with barrier* (see Figure 5-3)

Basic Cross-Sectional Geometry:



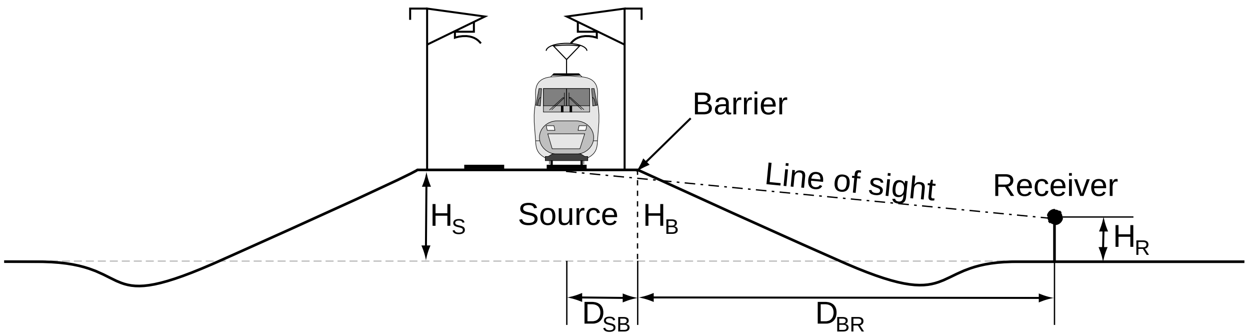
$$P = A + B - C$$

$$A = \sqrt{D_{SB}^{\,2} + \left(H_B - H_S\right)^2}$$

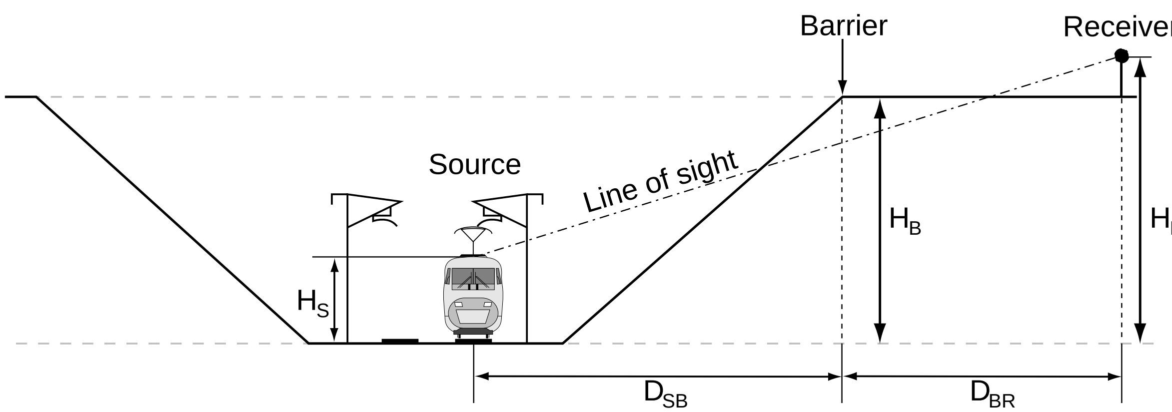
$$B = \sqrt{D_{BR}^{\,2} + \left(H_B - H_R\right)^2}$$

$$C = \sqrt{\left(D_{SB} + D_{BR}\right)^2 + \left(H_S - H_R\right)^2}$$

(a) Barrier Geometry for Edge of Embankment:



(b) Barrier Geometry for Depressed Tracks:



(c) Barrier Geometry for Earth Berm:

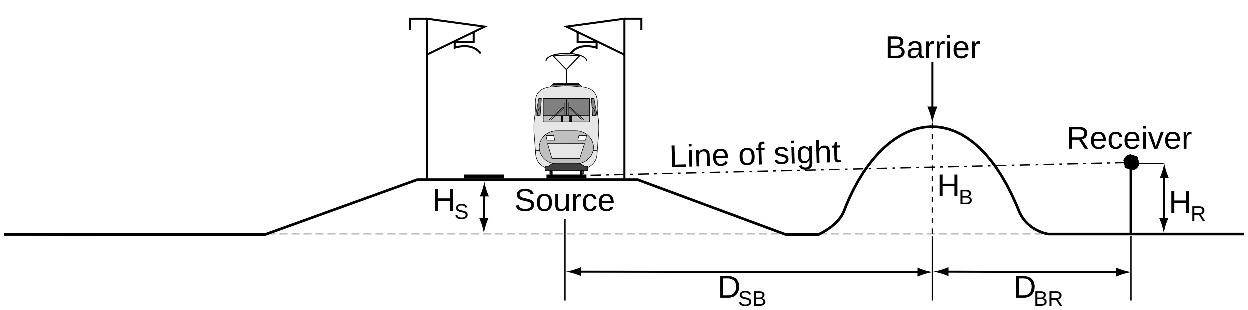


Figure 5-4 Barrier Geometry Models of Terrain for Computation of Shielding

4. Calculate SEL versus Distance: For each subsource SEL at 50 feet developed earlier in the analysis, plot a noise exposure-versus-distance curve, with SEL represented on the vertical axis and distance on the horizontal axis, by evaluating one of the following equations over a range of distances D:

$$SEL = SEL\big|_{\text{at 50 ft}} - 10\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{42}\right) - A_{shielding} \qquad \text{for wheel-rail subsources}$$

$$= SEL\big|_{\text{at 50 ft}} - 10\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{29}\right) - A_{shielding} \qquad \text{for propulsion subsources}$$

$$= SEL\big|_{\text{at 50 ft}} - 10\log\left(\frac{D}{50}\right) - A_{shielding} \qquad \text{for aerodynamic subsources.}$$

5.2.4 Step 6: Cumulative Noise Exposure

The procedures followed in Step 5 (Section 5.2.3) result in calculation of subsource SELs as a function of distance from the project corridor. The next step is to combine the subsources to yield a total SEL value for a train passby and convert from SEL to a measure of cumulative noise exposure based on a specific operating schedule. As guidance, a 40 percent change in either the number of trains per hour or the number of trains per day will produce an approximate 2-decibel change in cumulative noise exposure (L_{eq} or L_{dn}). The procedure is as follows:

1. Total Passby SEL: Calculate the total passby SEL by combining the subsource SELs obtained following Step 4 (Section 5.2.2), using the third equation in Table 5-4. The equations for subsource SEL at 50 feet and at distance *D* are repeated in Table 5-4 for clarity and to illustrate the continuity of the procedure.

2. Noise-Sensitive Hours: Determine the relevant time periods for all receivers that may be affected by the project. For residential receivers, the two time periods of interest for computation of L_{dn} are: daytime (7:00 a.m. to 10:00 p.m.) and nighttime (10:00 p.m. to 7:00 a.m.). For non-residential receivers, choose the loudest project hour during noise-sensitive activity. Several different hours may be of interest for non-residential receivers, depending on the hours the facility is used.

3. Train Operations: Determine number of trains per hour.

   For residential receivers:

   > V_d, the average hourly daytime (7 a.m. to 10 p.m.) train volume, and
   > V_n, the average hourly nighttime (10 p.m. to 7 a.m.) train volume.

   For non-residential receivers:

   > V, the hourly train volume for each hour of interest.

4. Hourly L_{eq}: Compute $L_{eq(h)}$ using the fourth equation in Table 5-4 for each hour of interest.

5. Day-Night Sound Level (L_{dn}): If the project noise will affect any residential receivers, compute the total train L_{dn} using the last three equations in Table 5-4.

Table 5-4 Computation of L_{eq} and L_{dn}

Quantity	**Equation**
n	
Subsource SEL at 50 ft:	$SEL_n = (SEL_{ref})_n + 10\log\left(\frac{len}{len_{ref}}\right)_n + K\log\left(\frac{S}{S_{ref}}\right)$
Subsource SEL at distance D:	$SEL_n = \begin{cases} SEL_n\Big\vert_{\text{at 50 ft}} - 10\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{42}\right) - A_{shielding} & \text{for Wheel/Rail Subsources} \\ SEL_n\Big\vert_{\text{at 50 ft}} - 10\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{29}\right) - A_{shielding} & \text{for Propulsion Subsources} \\ SEL_n\Big\vert_{\text{at 50 ft}} - 10\log\left(\frac{D}{50}\right) - A_{shielding} & \text{for Aerodynamic Subsources} \end{cases}$
***N* Subsources**:	
Total SEL for train passby:	$SEL = 10\log\left(\sum_{i=1}^{N} 10^{SEL_i/10}\right)$
Hourly Leq:	$L_{eq}(h) = SEL + 10\log(V) - 35.6 - A_{excess}$
Daytime L_{eq}:	$L_{eq}(day) = L_{eq}(h)\Big\vert_{V=V_d}$
Nighttime L_{eq}:	$L_{eq}(night) = L_{eq}(h)\Big\vert_{V=V_n}$
L_{dn}:	$L_{dn} = 10\log\left[15 \cdot 10^{L_{eq}(day)/10} + 9 \cdot 10^{(L_{eq}(night)+10)/10}\right] - 13.8$

$V =$ average hourly volume of train traffic, in trains per hour

$V_d =$ average hourly daytime volume of traffic, in trains per hour

$= \dfrac{\text{number of trains, 7 am to 10 pm}}{15}$

$V_n =$ average hourly nighttime volume of train traffic, in trains per hour

$= \dfrac{\text{number of trains, 10 pm to 7 am}}{9}$

† See Section 5.2.2 for definition of terms

6. Excess Shielding: If necessary, adjust for excess shielding. At this point, excess shielding (A_{excess}) that is site-specific and not directly related to the vertical geometry of the source relative to the receiver (as computed in Step 5) can be applied to the overall noise exposure. Such excess shielding can be caused by intervening rows of buildings, dense tree zones, and any other obstruction between the source and the receiver. The attenuations are applied to *overall* L_{eq} and L_{dn} and not to the individual subsource contributions. Equations for computing these attenuations are given in Table 5-5.

Table 5-5 Computation of Excess Shielding: Rows of Buildings and Dense Tree Zones

Condition	Equation
If gaps in the row of buildings constitute less than 35 percent of the length of the row:	$A_{buildings} = \min\{10 \text{ or } [1.5(R-1)+5]\}$
If gaps in the row of buildings constitute between 35 and 65 percent of the length of the row:	$= \min\{10 \text{ or } [1.5(R-1)+3]\}$
If gaps in the row of buildings constitute more than 65 percent of the length of the row:	$= 0$
Where at least 100 feet of trees intervene between source and receiver, *and* if no clear line-of-sight exists between source and receiver, *and* if the trees extend 15 feet or more above the line-of-sight:	$A_{trees} = \min\left\{10 \text{ or } \frac{W}{20}\right\}$
If above conditions do not occur:	$A_{trees} = 0$
NET ATTENUATION	$A_{excess} = \max\{A_{buildings} \text{ or } A_{trees}\}$

R = number of rows of houses that intervene between source and receiver
W = width of the tree zone along the line-of-site between source and receiver, in feet

An example of application of Steps 1 through 6 of the Detailed Noise Analysis procedure for a hypothetical proposed high-speed rail project follows.

Example 5-1. Detailed Noise Projection Procedure

Consider the following system:

Proposed Equipment: The project will use a steel-wheeled electric train with 2 power cars (one on each end) and 8 passenger coaches. The maximum design speed will be 180 mph, placing it in the "Very High-Speed" category in Table 5-2. The locomotives are 73 feet long each, and the cars are each 61 feet long.

Proposed Service: Hours of revenue service from 5:00 a.m. to midnight. Hourly volumes are:

Daytime (7 a.m. to 10 p.m.):

V_d = 4 trains/hour

Nighttime (10 p.m. to 12 p.m., 5 a.m. to 7 a.m.):

V_n = 1 train/hour

In the corridor segment of concern, the train will pass through a shallow cut with sloped walls, and we are concerned with the sound exposure at a 5-foot receiver standing 80 feet from the edge of the cut (200 feet from the centerline of the near track).

The geometry is illustrated in case 3 of Figure 5-3, with the following parameter values:

A = 105 feet
B = 200 feet
H_r = 5 feet
H_c = 49 feet
H_b = 0 feet, and
H_s = subsource heights as given in Table 5-2 for Very High-Speed trains.

1. Calculate the ground factor, G, for the wheel-rail and propulsion subsources using the equations in Figure 5-3:

$$H_{eff} = \frac{H_s+2H_b+H_c+H_r}{2}$$

$$= \frac{(1)+(2\times 0)+(49)+(5)}{2} = 27.5 \text{ for wheel-rail}$$

and, $$H_{eff} = \frac{(12)+(2\times 0)+(49)+(5)}{2} = 33 \text{ for propulsion.}$$

Using the equation for G, again from Figure 5-3,

$$G = .75\left(1-\frac{H_{eff}}{42}\right)$$

$$= .75\left(1-\frac{27.5}{42}\right) = .26 \text{ for wheel-rail}$$

and, $$= .75\left(1-\frac{33}{42}\right) = .16 \text{ for propulsion.}$$

2. Since the line of sight between the receiver and the source may be broken by the cut (see Figure 5-4(b)), determine the shielding due to the terrain. Using the geometry from Table 5-3, with the barrier height represented by the height of the cut,

D_{SB} = 120 feet,
D_{BR} = 80 feet,
H_R = 54 feet (receiver height + height of cut),
H_B = 49 feet, and
H_S = heights of wheel-rail, propulsion, and aerodynamic subsources from Table 5-2.

Use these values to obtain the lengths A, B, C, and P in Table 5-3:

	Propulsion	Wheel-Rail	Train Nose	Wheel Region	Pantograph
A	125.6	129.2	126.2	127.8	124.7
B	80.2	80.2	80.2	80.2	80.2
C	204.4	206.9	204.8	205.9	203.8
P	1.4	2.5	1.6	2.1	1.1

Insert the path length difference, P, into the equations for Barrier Attenuation from Table 5-3, which yields:

$A_{barrier,propulsion}$ = 14.4,
$A_{barrier,wheel-rail}$ = 20.0,
$A_{barrier,train\ nose}$ = 8.9,
$A_{barrier,wheel\ region}$ = 10.1, and
$A_{barrier,pantograph}$ = 7.6.

Solve for the insertion loss using the fourth equation in Table 5-3. Because this system does not have a man-made barrier, set G_{NB} and G_B=0. This yields:

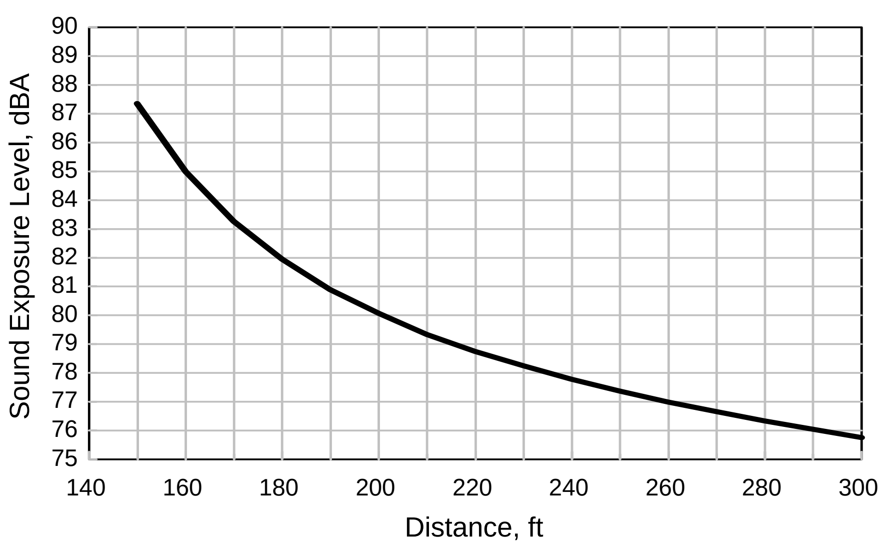
$A_{shielding,propulsion}$ = 14.4,
$A_{shielding,wheel-rail}$ = 20.0,
$A_{shielding,train\ noise}$ = 8.9,
$A_{shielding,wheel\ region}$ = 10.1, and
$A_{shielding,pantograph}$ = 7.6.

3. To calculate the noise exposure as a function of distance, normalize the reference quantities in Table 5-2 to the actual operating conditions of the proposed system, using the method from Section 5.2.2. This results in the following subsource SELs:

   Propulsion = 89 dBA,
   Wheel-rail = 97 dBA,
   Train nose = 92 dBA,
   Wheel region = 89 dBA, and
   Pantograph = 86 dBA.

   Using these values, evaluate the equations in section 5.2.3 at a distance of 200 feet at each subsource. Add the subsource SELs together to obtain the total SEL exposure. A plot of the total SEL versus distance for this example is given below. At 200 feet, the sound exposure level at the receiver will be about 80 dBA.

SEL vs. Distance
Train in Cut



4. Using the L_{eq} and L_{dn} equations in Table 5-4, compute the cumulative noise exposure at the receiver:

L_{eq}(day) = 51 dBA,
L_{eq}(night) = 45 dBA, and
L_{dn} = 52 dBA.

End of Example 5-1

5.2.5 Step 7: Maximum Noise Level for Train Passbys

Noise impact assessment in this manual is based on either L_{dn} or L_{eq}; therefore, normally it is not necessary to determine and tabulate the maximum levels (L_{max}). However, often it is desirable to include estimates of L_{max} since:

- it is representative of what people hear at any particular instant;
- it is straightforward to measure with a standard sound level meter;
- noise limits in vehicle specifications are usually in terms of L_{max}; and
- because L_{max} represents the sound level heard during a transportation vehicle passby, people can related this metric with other environmental noises, such as an aircraft flyover or a truck passby.

Although L_{max} is not used in this manual as a basis for assessing noise impact, when used in conjunction with L_{eq}(h) or L_{dn} it can provide a more complete description of the noise effects of a proposed project. L_{max} also may be necessary in determining compliance with the project noise limits. Equations for computing L_{max} from SEL and also for estimating a single reference SEL (for use in the General Assessment method presented in Chapter 4) from a specified or measured value of L_{max} are given in Appendix C. Application of these equations is illustrated in Example 5-2.

Example 5-2. Calculation of L_{max} using Detailed Noise Analysis Procedure

This example demonstrates how to compute L_{max} combining the methods described in Chapter 5 and the equations given in Appendix C. The segment in question will utilize an electric locomotive-hauled train with a maximum design speed of 150 mph, which places it in the "high speed" category of Table 5-2. The land abutting the rail corridor is flat with no shielding, and the tracks are on a 3-foot high embankment. The receiver is assumed to be 5 feet high, and the noise specification requires L_{max} at a distance of 50 feet away from the centerline of the tracks. The trainset is made up 2 power units (one at each end of the set) and 10 passenger coaches. The parameters for this train are,

$SEL_{ref,propulsion}$ = 86 dBA,

$SEL_{ref,wheel-rail}$ = 91 dBA,

N_{locos} = 2,

N_{cars} = 10,

L_{locos} = 73 feet,

L_{cars} = 61 feet,

$L_{total,locos}$ = 146 feet,

$L_{total,cars}$ = 610 feet,

S= 150 mph, and

D= 50 feet.

The SELs for each subsource must be computed for the proposed consist and speed using the methods described in section 5.2. Then, L_{max} from each subsource can be calculated using the equations in Appendix C. The highest subsource L_{max} is used in the noise specification for this trainset.

First, the effective path heights must be calculated to determine the ground attenuation. As shown in Figure 5-3, the effective ground height is

$$H_{eff} = (H_s+2H_b+H_r)/2$$

so H_{eff} = 4.5 for the wheel-rail subsource, and
H_{eff} = 9 for the propulsion subsource.

This corresponds to

G = .66 for the wheel-rail subsource, and
G = .59 for the propulsion subsource.

The reference parameters given in Table 5-2 must now be adjusted to actual speed and distance conditions by using the equations from section 5.2.2. It should be noted that for cases where the locomotives are located on opposite ends of the train, they should be treated separately; the equations in Section 5.2.2 assume the locomotives are in groups. In other words,

$$\begin{aligned} SEL_{propulsion} &= SEL_{ref,propulsion}+10\log(73/73)+15\log(150/20) \\ &= 99.1 \end{aligned}$$

for <u>each</u> power unit, and

$$\begin{aligned} SEL_{wheel/rail} &= SEL_{ref,wheel/rail}+10\log((146+610)/634)+20\log(150/90) \\ &= 96.2 \end{aligned}$$

for the wheel/rail component of the train.

Using the equations in section 5.2.3, the SEL at 50 feet for each power unit is:

$$SEL = SEL_{propulsion} - 10\log\left(\frac{D}{50}\right) - 10G\ \log\left(\frac{D}{29}\right),\ \text{which yields}$$

$$SEL = 99.1 - 10\log\left(\frac{50}{50}\right) - 10(.59)\log\left(\frac{50}{29}\right) = 97.7$$

and for the wheel-rail subsource is:

$$SEL = SEL_{wheel/rail} - 10\log\left(\frac{D}{50}\right) - 10G\ \log\left(\frac{D}{42}\right),\ \text{which yields}$$

$$SEL = 96.2 - 10\log\left(\frac{50}{50}\right) - 10(.66)\log\left(\frac{50}{42}\right) = 95.7$$

These SELs can now be used in the equations given in Table C-1. First, α corresponding to propulsion and wheel/rail noise must be calculated:

α = arctan (L/2D)
= .63 for propulsion noise and
= 1.4 for wheel/rail noise.

Then,

$L_{max,propulsion}$ = 97.7-10log(73/150)+10log(2×.63)-3.3
= 98.5 dBA, or 99 dBA (rounded)

$L_{max,wheel/rail}$ = 95.7-10log(610/150)+10log[(2×1.44)+sin(2×1.44)]-3.3
= 91.3 dBA, or 91 dBA (rounded).

The total L_{max} is the largest of the two:

$L_{max,total}$ = 99 dBA.

End of Example 5-2

5.3 STEP 8: NOISE IMPACT ASSESSMENT

This section outlines procedures for assessing noise impact using the existing and projected noise results developed using the methodologies described in the previous sections. These procedures can be applied not only to noise impact from high-speed rail operations, including projects built within a highway or railroad corridor, but also to impacts from fixed facilities such as storage and maintenance yards, passenger stations and terminals, parking facilities, and substations.

5.3.1 Assessment Procedure

Noise impact should be assessed at each receiver of interest using the criteria for high-speed rail projects described in Chapter 3 as follows:

1. **Existing Noise Exposure**. Tabulate existing ambient noise exposure (rounded to the nearest whole decibel) at all receivers of interest identified earlier in the analysis.

2. **Project Noise Exposure**. Tabulate project noise exposure at these receivers using the analytical procedures described in this chapter. In the tabulation, account for added annoyance from startle for receivers located within the distances given in Figure 4-2 (Chapter 4).

3. **Noise Impact Criteria**. Determine the level of noise impact (No Impact, Impact or Severe Impact) by comparing the existing and project noise exposure based on the impact criteria in Chapter 3.

4. **Noise Impact Inventory**. Document the results in noise-assessment inventory tables. These tables should include the following types of information:

   - receiver identification and location,
   - land-use description,

- number of noise-sensitive sites represented (usually the number of residential buildings or dwelling units),
- closest distance to the project,
- existing noise exposure,
- project noise exposure,
- level of noise impact (No Impact, Impact or Severe Impact), and
- potential for startle.

In addition, these tables should indicate the total number of receivers predicted to experience Impact or Severe Impact.

5. **Graphical Illustration of Noise Impact**. Illustrate the areas of Impact and Severe Impact on maps or aerial photographs. This illustration could consist of noise impact contours on the maps or aerial photographs, along with the impact areas highlighted. This is done by delineating two impact lines: one between the areas of No Impact and Impact and the second between Impact and Severe Impact. To conform with the practices of another agency (e.g., FHWA, FAA), include several contour lines of constant project noise, such as L_{dn} 65, L_{dn} 70 and L_{dn} 75.

6. **Magnitude of Noise Impact**. Determine the magnitude of the impacts as the basis of the assessment, defined by the two threshold curves delineating onset of Impact and Severe Impact. Interpretation of the two impact regimes is discussed in Chapter 3.

7. **Maximum Noise Level**. Evaluate and tabulate L_{max} at sensitive receivers and locations where SEL exceeds the interim criteria for effects on animals as discussed in Chapter 3.

5.3.2 Example of GIS Implementation

Geographic Information System (GIS) technology can be a useful tool in graphically identifying and displaying noise impacts, as well as simplifying the mapping and inventorying work that is needed to complete the impact assessment. While development of a GIS method was not within the scope of this manual, an example showing a conceptual method of implementing GIS is given in this section.

The GIS example utilizes the parameters of Alignment Alternative 1 in Example 4-1 (Chapter 4). This corridor will use a high-speed electric trainset with a maximum speed of 180 mph, passing through a rural area with scattered residences, as shown in Figure 5-5.

Procedure

The screening procedure calls for further analysis for noise-sensitive land use within 1,000 feet of a new corridor. Using GIS, the procedure is as follows:

Step 1. **Digitize GIS Input Map**. Input a diagram of the project area into the GIS by digitizing a map, using aerial or satellite photography, CAD, or other methods. The GIS will determine grade crossings, embankments and cuts from topographic contours. Environmental features such as dense foliage are selected by choosing the appropriate icon and applying the feature to the map.

Step 2. **Identify the sensitive receivers**. Identify and label all sensitive land uses by address and owner, either manually, or by importing the information from a database. Distances from each receiver to the track will be computed automatically.

Step 3. **Input train parameters**. Obtain train data such as speed, type and number of cars for input to the noise propagation model, which is linked to the GIS. As demonstrated in Example 4-1 (Chapter 4), the onset for impact and severe impact is 990 and 350 feet, respectively. The GIS will automatically calculate the distances for impact and severe impact, and draw the noise contours as shown in Figure 5-5.

Step 4. **Assess impact at specific receivers**. Predictions of noise and vibration levels at specific receivers will also be calculated automatically using the noise contour information obtained. To view statistics for a certain residence, select the residence and a dialog box will appear, providing receiver information including address, owner, and projected noise and vibration levels from high-speed trains.

Step 5. **Input new parameters**. To view the effects of different train configurations and/or speeds, input the new parameters into the GIS and the model will redraw new impact contours and update the noise and vibration levels at each receiver.

Once the receiver and geographic information has been entered into the system, it is possible to change any number of variables, including track position, train configuration, and shielding and receive updated noise and vibration predictions with little effort. Use of GIS technology also allows residents who live near a corridor to see the specific impact that a rail project would have on them.

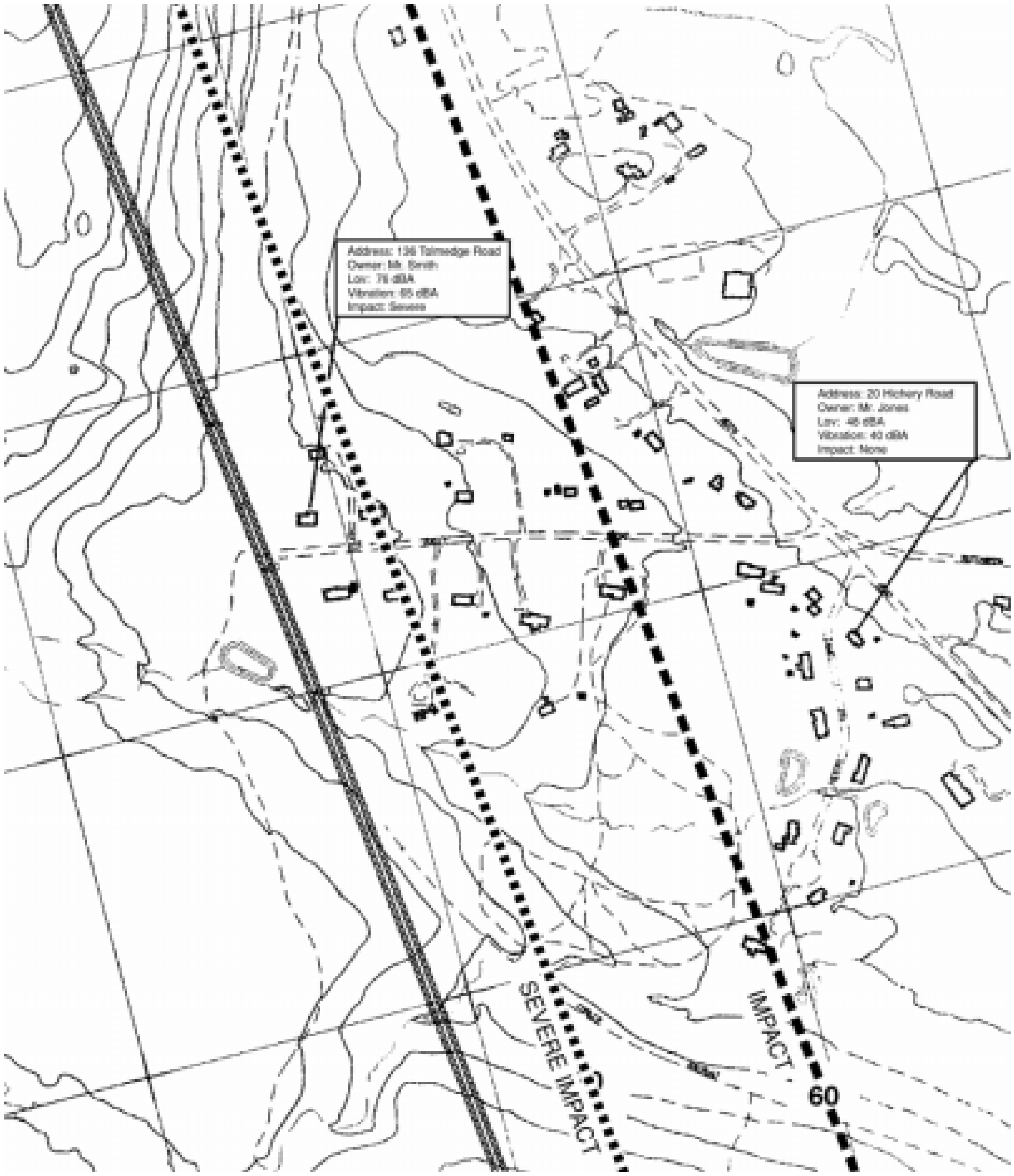


Figure 5-5 Determining Noise Impact using GIS

5.4 MITIGATION OF NOISE IMPACT

This section provides guidance for evaluating noise reduction measures at locations where the noise impact assessment shows either Severe Impact or Impact. In general, mitigation options are chosen from those listed below, and then relevant portions of the project noise are recomputed and reassessed to account for this mitigation. This reassessment provides an accurate prediction of the noise reduction and the resulting net impact of the project, assuming the incorporation of mitigation measures either in the initial project plans by the project proponent, or as a condition imposed by the approving public agency.

The source levels used in this manual are typical of high-speed rail systems designed according to current engineering practice, but they do not include special noise control features that could be incorporated in the specifications at extra cost (e.g., wheel skirts, pantograph shrouds). Such measures could further reduce noise impact and warrant consideration by project proponents and public agencies where the Initial Noise Evaluation indicates the potential for extensive areas of severe impact.

Mitigation of noise impact from high-speed rail projects may involve treatments at the three fundamental components of the noise problem: (1) at the noise source, (2) along the source-to-receiver propagation path, or (3) at the receiver. A list of practical noise mitigation measures that should be considered is summarized in Table 5-6. This table is organized according to whether the treatment applies to the source, path, or receiver, and includes estimates of the acoustical effectiveness of each treatment. The treatments are discussed in Sections 5.4.1 through 5.4.3. Note the mitigation treatments are not additive within each group. Professional judgement is required to determine the total effectiveness, but one can usually add the effectiveness of one treatment from each group.

5.4.1 Source Treatments

Vehicle Noise Specifications

Incorporating noise control features during the specification and design of the vehicle is among the most effective noise mitigation treatments. The development and enforcement of stringent but achievable noise specifications by the project sponsor is a major step in controlling noise everywhere on the system. It is important to ensure that noise levels quoted in the specifications are achievable with the application of best available technology during the development of the vehicle and reasonable in light of the noise reduction benefits and costs. Effective enforcement includes imposing significant penalties for noncompliance with the specifications.

Wheel Treatments

A major source of noise from steel-on-steel high-speed rail systems is the wheel-rail interaction, which has three components: roar, impact, and squeal. Roar is the rolling noise caused by small-scale roughness on the wheel tread and rail running surface. Impacts are caused by discontinuities in the running surface of the rail or by flat spots on the wheels. Squeal occurs when a steel-wheel tread or its flange rubs across the rail, setting up resonant vibrations in the wheel, which cause it to radiate a screeching sound.

Various wheel designs and other mitigation measures to reduce the noise from each of these three mechanisms include:

- **Resilient and damped wheels** to reduce rolling noise, but only slightly. A typical reduction is 2 decibels on tangent track. This treatment is more effective in eliminating wheel squeal in tight curves; reductions of 10 to 20 decibels for high frequency squeal noise is typical.
- **Spin-slide control systems,** similar to anti-locking brake systems on automobiles, reduce the incidence of wheel flats (localized flat spots on wheels), a major contributor of impact noise. Trains with smooth wheel treads can be up to 20 decibels quieter than those with wheel flats. To be effective, the anti-locking feature should be in operation during all braking phases, including emergency braking. Wheel flats are more likely to occur during emergency braking than during dynamic braking.
- **Maintenance** of wheels by truing eliminates wheel flats from the treads and restores the wheel profile. An effective maintenance program includes the installation of equipment to detect and correct wheel flats on a continuing basis.

<table>
<tr><th colspan="4">Table 5-6 High Speed Rail Noise Mitigation Measures</th></tr>
<tr><th>Application</th><th colspan="2">Mitigation Measure</th><th>Effectiveness</th></tr>
<tr><td rowspan="16">SOURCE</td><td colspan="2">Stringent Vehicle & Equipment Noise Specifications</td><td>Varied</td></tr>
<tr><td colspan="2">Placement of HVAC systems</td><td>Varied</td></tr>
<tr><td colspan="2">Sound-Absorptive Duct Lining for Air Intake/Exhaust</td><td>Varied</td></tr>
<tr><td colspan="2">Operational Restrictions</td><td>Varied</td></tr>
<tr><td rowspan="2">Resilient or Damped Wheels</td><td>For Rolling Noise on Tangent Track:</td><td>2 dB</td></tr>
<tr><td>For Wheel Squeal on Curved Track:</td><td>10-20 dB</td></tr>
<tr><td colspan="2">Vehicle Skirts</td><td>6-10 dB</td></tr>
<tr><td colspan="2">Under-car Absorption</td><td>5 dB</td></tr>
<tr><td colspan="2">Spin-slide control (prevents flats)</td><td>**</td></tr>
<tr><td colspan="2">Wheel Truing (eliminates wheel flats)</td><td>**</td></tr>
<tr><td colspan="2">Rail Grinding (eliminates corrugations)</td><td>**</td></tr>
<tr><td colspan="2">Turn Radii greater than 1000 ft</td><td>(Avoids Squeal)</td></tr>
<tr><td colspan="2">Rail Lubrication on Sharp Curves</td><td>(Reduces Squeal)</td></tr>
<tr><td colspan="2">Movable-point Frogs (reduce rail gaps at crossovers)</td><td>(Reduces Impact Noise)</td></tr>
<tr><td colspan="2">Elimination of all surface discontinuities/edges on Vehicle Body</td><td>3-6 dB</td></tr>
<tr><td colspan="2">Pantograph cover or shroud</td><td>5 dB</td></tr>
<tr><td rowspan="7">PATH</td><td colspan="2">Sound Barriers close to Vehicles</td><td>6-10 dB</td></tr>
<tr><td colspan="2">Sound Barriers at ROW Line</td><td>5-8 dB</td></tr>
<tr><td colspan="2">Alteration of Horizontal & Vertical Alignments</td><td>Varied</td></tr>
<tr><td colspan="2">Acquisition of Buffer Zones</td><td>Varied</td></tr>
<tr><td colspan="2">Ballast on At-Grade Guideway</td><td>3 dB</td></tr>
<tr><td colspan="2">Ballast on Aerial Guideway</td><td>5 dB</td></tr>
<tr><td colspan="2">Resilient Track Support on Aerial Guideway</td><td>Varied</td></tr>
<tr><td rowspan="2">RECEIVER</td><td colspan="2">Acquisition of Property Rights for Construction of Sound Barriers</td><td>5-10 dB</td></tr>
<tr><td colspan="2">Building Noise Insulation</td><td>5-20 dB</td></tr>
<tr><td colspan="4">** These mitigation measures work to maintain a high-speed rail system in its as-new condition. Without incorporating them into the system, noise levels could increase by up to 10 dB.</td></tr>
</table>

Vehicle Treatments

Vehicle noise mitigation measures are applied to the various mechanical systems associated with propulsion, ventilation, and passenger comfort; these include:

- **Propulsion systems** of high-speed rail vehicles include electric traction motors and fossil fuel turbine engines. Noise from the propulsion system depends on the type of unit and the level of noise mitigation is built into the design.
- **Ventilation** requirements for vehicle systems are related to the noise generated by a vehicle. Fan noise often remains a major noise source after other mitigation measures have been instituted

because of the need to have direct access to cooling air. This problem applies to heat exchangers for electric traction motors and air-conditioning systems. Fan quieting can be accomplished by installation of one of several new designs of quiet, efficient fans. Forced-air cooled electric traction motors can be quieter than self-cooled motors at operating speeds. Placement of fans on the vehicle can make a significant difference in the noise radiated to the wayside or to patrons on the station platforms.

- The **vehicle body** design can provide shielding and absorption of the noise generated by the vehicle components. Acoustical absorption under the car has been demonstrated to provide up to 5 decibels of mitigation for wheel-rail noise and propulsion-system noise on rapid transit trains.[5] Similarly, vehicle skirts over the wheels can provide more than 5 decibels of mitigation. By providing their own noise barriers, vehicles with these features can provide cost-effective noise reduction.

Guideway Support

The smoothness of the running surface is critical in the mitigation of noise from a moving vehicle. Due to the high train speeds, smooth rail running surfaces are essential for controlling noise at acceptable levels on high-speed rail systems. Roughness of rail surfaces can be eliminated by grinding rails, thereby reducing noise levels by up to 10 decibels.

Operational Restrictions

Restrictions on operations are not a desirable mitigation option because of service demands. However, in extreme cases they can be a viable option. Two changes in operations that can mitigate noise are decreasing speed in selected, noise-sensitive areas and reducing nighttime (10 p.m. to 7 a.m.) operations. Because noise from high-speed trains depends on speed, a reduction of speed results in lower noise levels. The effect can be considerable. For example, each halving of speed on a steel-wheel/steel-rail system results in a 6 dB reduction in noise exposure (see Table 5-2). Complete elimination of nighttime operations has a strong effect on reducing the L_{dn}, because nighttime noise is increased by 10 decibels when calculating L_{dn}.

It is expected that most new high-speed rail systems will be grade-separated, eliminating the need for grade crossings and their associated noise levels. However, when grade crossings are present in lower-speed track segments, other operational restrictions that can reduce noise impact include minimizing or eliminating horn blowing and other types of audible warning signals. These mitigation options must be compliant with safety regulations and FRA guidelines.

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[5] C.E. Hanson, "Noise Control for Rapid Transit Cars on Elevated Structures," *Journal of Sound and Vibration 87(2)*: 285-294 (1983).

5.4.2 Path Treatments

Sound Barriers

Sound barriers are probably the most common noise mitigation measure used in surface transportation modes. Sound barriers are effective in mitigating noise when they break the line-of-sight between source and receiver. The mechanism of sound shielding is described in Chapter 2. The necessary height of a barrier depends on factors such as the source height and the distance from the source to the barrier. For example, a barrier located very close to the nearest track need only be 3 to 4 feet above the top of rail to effectively reduce wheel-rail noise, providing noise reductions of 6 to 10 decibels. The height of barriers farther away from the adjacent track, such as on the right-of-way line or for trains on the far track, or for screening aerodynamic noise sources, must be increased to provide equivalent effectiveness. Otherwise, the effectiveness of the barrier could drop to 5 decibels or less, even if it breaks the line of sight. Where the barrier is very close to the vehicle or where the vehicles travel between sets of parallel barriers, barrier effectiveness can be increased by as much as 5 decibels by applying sound-absorbing material to the inner surface of the barrier.

Similarly, the length of the barrier wall is important in its effectiveness. The barrier must be long enough to screen out a moving train along most of its visible path. This length is necessary so that train noise from beyond the ends of the barrier will not severely compromise noise-barrier performance at sensitive locations.

Noise barriers can be made of any outdoor weather-resistant solid material that meets a minimum sound transmission loss requirement. The sound requirements are not particularly strict; they can be met by many commonly available materials, such as 16-gauge steel, 1-inch-thick plywood, and any reasonable thickness of brick or concrete. The normal minimum requirement is a surface density of 4 pounds per square foot. To sustain wind loads, structural requirements are more stringent. Most importantly, achieving the maximum possible noise reduction requires careful sealing of gaps between barrier panels and between the barrier and the ground or elevated guideway deck.

Costs for noise barriers, based on highway installations, range from $15 to $25 per square foot of installed noise barrier at-grade, not counting design and construction inspection costs. The cost of installation on an aerial structure is approximately the same as at-grade, unless the structure has to be strengthened to accommodate the added weight and wind load.

Locating a rail alignment in a reasonably deep cut or trench, as part of a grade separation, can accomplish the same result as installing a noise barrier. The walls of the trench serve the same function as barrier walls in breaking the line-of-sight between source and receiver.

Noise Buffers

Because noise levels attenuate with distance, increasing the distance between noise sources and the closest sensitive receivers can be an effective mitigation measure. This buffer can be accomplished by locating alignments away from sensitive sites. In areas of severe impact, acquiring land or easements for noise buffer zones is an option that may be considered.

Ground Absorption

Propagation of noise over ground is affected by whether the ground surface is absorptive or reflective. Noise from vehicles at-grade is strongly affected by the character of the ground in the immediate vicinity of the vehicle. Guideways for rail systems can be either reflective or absorptive, depending on whether they are concrete or ballast. Ballasted track construction can reduce train noise 3 decibels at-grade and up to 5 decibels on aerial structure.

5.4.3 Receiver Treatments

Sound Barriers

In certain cases it may be possible to acquire limited property rights for the construction of sound barriers at the receiver. As discussed above, barriers need to break the line of sight between the noise source and the receiver to be effective and are most effective when they are closest to either the source or the receiver. Procedures for estimating barrier effectiveness are given earlier in this chapter.

Building Insulation

In cases where rights-of-way are restricted, the only practical noise mitigation measure may be to provide sound insulation for the building. The most effective treatments are to caulk and seal gaps in the building envelope and to install windows that are specially designed to meet acoustical transmission-loss requirements. These windows are usually made of multiple layers of glass and are beneficial for heat insulation as well as for sound insulation. Depending on the quality of the original windows, the new windows can provide noise reductions of 5 to 20 decibels. Such windows are usually nonoperable so that central ventilation or air conditioning would be needed. Additional sound insulation, if needed, can be provided by sealing vents and ventilation openings and relocating them to a side of the building away from the noise source.

Chapter 6

GROUND-BORNE VIBRATION CONCEPTS

Noise and vibration are traditionally linked in environmental impact assessments because the two disciplines are perceived to have many physical characteristics in common. For example, noise can be generated by vibration of surfaces. Both involve fluctuating motion: noise is oscillating motion of air and vibration is oscillating motion of structures or the ground. Both are analyzed as wave phenomena: noise is made up of sound waves in air and vibration travels as waves in the ground. Both are measured in decibels. Both are considered sensory effects: noise is related to hearing and vibration is related to feeling. Despite their similarities, however, noise and vibration require entirely different kinds of analyses. The fact that ground-borne vibration travels through a succession of solid media, such as various kinds of soil, rock, building foundation, and building structure, to reach the receiver makes vibration more complicated to measure and to predict than noise.

This chapter provides a general background on ground-borne vibration and summarizes the available data on ground-borne vibration caused by high-speed trains. The focus is on vibration generated by steel-wheel trains.[1] The material presented is based largely on empirical data, since ground-borne vibration is a more complex phenomenon than that of airborne noise. The information contained in this chapter forms the basis of the assessment procedures presented in Chapters 7, 8, and 9.

The effects of ground-borne vibration include perceptible movement of the building floors, rattling of windows, shaking of items on shelves or hanging on walls, and rumbling sounds. In extreme cases, such vibration can damage buildings and other structures. Building damage is not a factor for most surface

[1]Because maglev systems do not touch the guideway except when stationary, the ground-borne vibration forces are much lower than with steel-wheel trains. Although there is some ground-borne vibration generated by the fluctuating magnetic forces, the vibration forces are generally low enough that ground-borne vibration from maglev trains can be ignored.

transportation projects, except during construction when there may be occasional blasting and pile driving. Annoyance from vibration often occurs when the vibration exceeds the threshold of perception by 10 decibels or less. This vibration level is an order of magnitude below the damage threshold for normal buildings.

The basic concepts of ground-borne vibration are illustrated for a high-speed rail system in Figure 6-1. The train wheels rolling on the rails create vibration energy transmitted through the track support system into the trackbed or track structure. The amount of energy that is transmitted into the track structure depends strongly on factors such as how smooth the wheels and rails are and the resonance frequencies of the vehicle suspension system and the track support system.

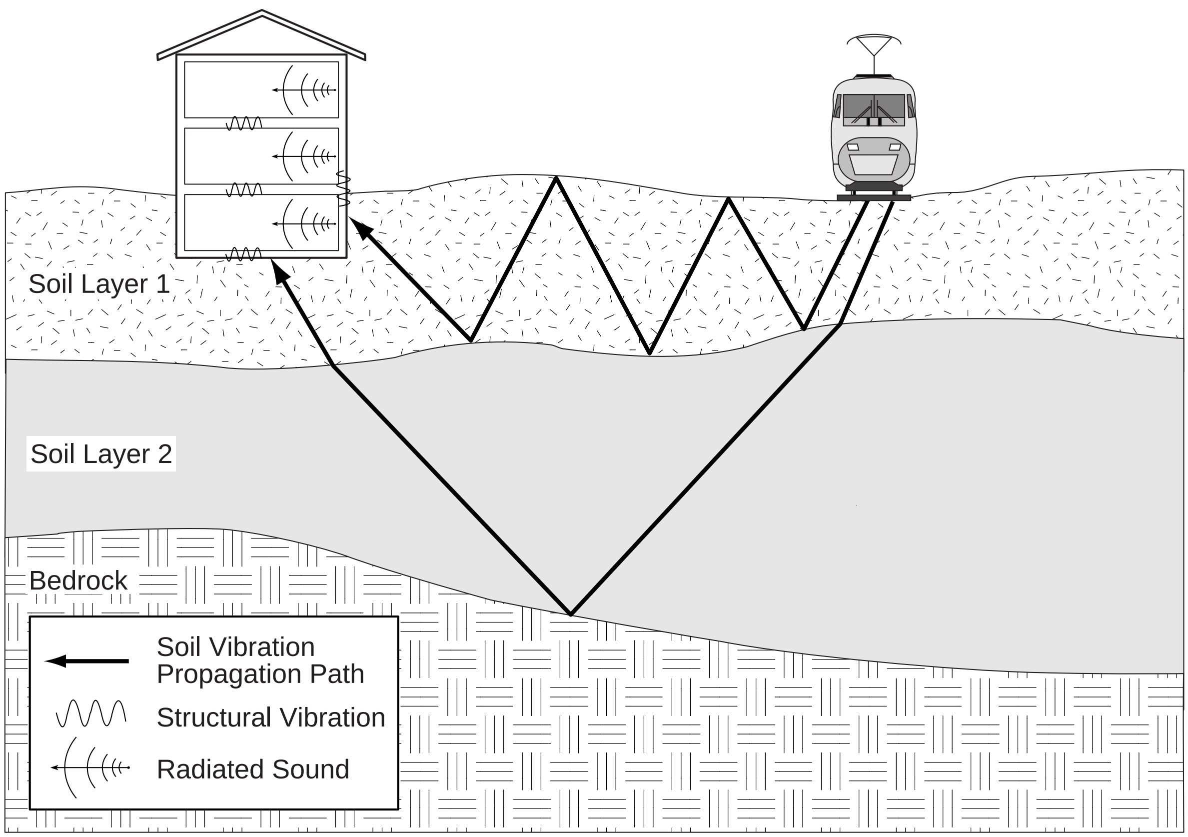

Figure 6-1 Propagation of Ground-Borne Vibrations into Buildings

The vibration of the rail structure excites the adjacent ground, creating vibration waves that propagate through the various soil and rock strata to the foundations of nearby buildings. The vibration propagates from the foundation throughout the remainder of the building structure. The maximum vibration amplitudes of floors and walls of a building often occur at the resonance frequencies of those building elements.

The vibration of floors and walls may cause perceptible vibration, rattling of items such as windows or dishes on shelves, or a rumble noise. The rumble is the noise radiated from the motion of the room surfaces. In essence, the room surfaces act like a giant loudspeaker. This is called ground-borne noise.

Ground-borne vibration is almost never annoying to people who are outdoors. Although the motion of the ground may be perceived, the motion does not provoke the same adverse human reaction without the effects associated with the shaking of a building. In addition, the rumble noise that usually accompanies the building vibration can only occur inside buildings.

6.1 DESCRIPTORS OF GROUND-BORNE VIBRATION AND NOISE

6.1.1 Vibratory Motion

Vibration is an oscillatory motion, which can be described in terms of displacement, velocity, or acceleration. Because the motion is oscillatory, there is no net movement of the vibration element, and the average of any of the motion descriptors is zero. Displacement is the easiest descriptor to understand. For a vibrating floor, the displacement is simply the distance that a point on the floor moves away from its static position. The velocity represents the instantaneous speed of the floor movement, and acceleration is the rate of change of the speed.

Although displacement is easier to understand than velocity or acceleration, it is rarely used to describe ground-borne vibration. This is because most transducers used for measuring ground-borne vibration use either velocity or acceleration, and, even more important, the response of humans, buildings, and equipment to vibration is more accurately described using velocity or acceleration.

6.1.2 Amplitude Descriptors

Vibration consists of rapidly fluctuating motions with an average motion of zero. The various methods used to quantify vibration amplitude are shown in Figure 6-2. The raw signal is the lighter weight curve in the top graph. This is the instantaneous vibration velocity, which fluctuates about the zero point. The peak particle velocity (PPV) is defined as the maximum instantaneous positive or negative peak of the vibration signal. PPV often is used in monitoring of blasting vibration since it is related to the stresses that are experienced by buildings.

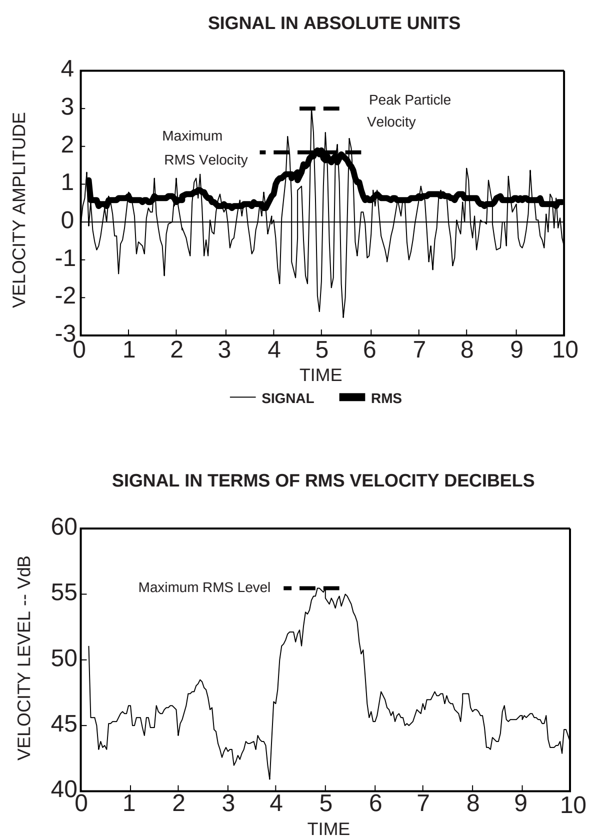

Figure 6-2 Different Methods of Describing a Vibration Signal

Although PPV is appropriate for evaluating the potential of building damage, it is not suitable for evaluating human response. It takes some time for the human body to respond to vibration signals. In a sense, the human body responds to an average vibration amplitude. Because the net average of a vibration signal is zero, the root mean square (RMS) amplitude is used to describe the "smoothed" vibration amplitude. The RMS of a signal is the average of the squared amplitude of the signal. The average is typically calculated over a 1-second period. The RMS amplitude is shown superimposed on the vibration signal in Figure 6-2. The RMS amplitude is always less than the PPV and is always positive.[2]

The PPV and RMS velocities are normally described in inches per second in the U.S. and in meters per second in the rest of the world. Although it is not universally accepted, decibel notation is in common use for vibration. Decibel notation serves to compress the range of numbers required to describe vibration. The bottom graph in Figure 6-2 shows the RMS curve of the top graph expressed in decibels. Vibration velocity level in decibels is defined as:

$$L_v = 20 \times \log_{10}\left(\frac{v}{v_{ref}}\right)$$

where "L_v" is the velocity level in decibels, "v" is the RMS velocity amplitude, and "v_{ref}" is the reference velocity amplitude. A reference always must be specified whenever a quantity is expressed in terms of decibels. The accepted reference quantities for vibration velocity are $1\text{x}10^{-6}$ in./sec in the U.S. and either $1\text{x}10^{-8}$ m/sec or $5\text{x}10^{-8}$ m/sec in the rest of the world. Because of the variations in the reference quantities, it is important to state clearly the reference quantity being used whenever velocity levels are specified. ***All** vibration levels in this manual are referenced to 1x10^{-6} in./sec.* Although not a universally accepted notation, the abbreviation "VdB" is used in this document for vibration decibels to reduce the potential for confusion with sound decibels.

A standardized weighted vibration level has been used in Japan to evaluate human response to vibration. This vibration level, often abbreviated VL, is usually referred to as the *weighted acceleration level*. At frequencies greater than 8 Hz, which for all practical purposes is the frequency range of interest for ground-borne vibration:

$$VL \approx L_v - 21$$

where L_v is the vibration velocity level in decibels relative to 1 micro-inch per second (10^{-6} in./sec).

6.1.3 Ground-Borne Noise

As discussed above, the rumbling sound caused by the vibration of room surfaces is called ground-borne noise. The annoyance potential of ground-borne noise is usually characterized using the A-weighted sound level. Although the A-weighted level is almost the only descriptor for community noise, there are potential problems when characterizing low-frequency noise using A-weighting. This is because of the

[2] The ratio of PPV to maximum RMS amplitude is defined as the **crest factor** for the signal. The crest factor is always greater than 1.71, although a crest factor of 8 or more is not unusual for impulsive signals. For ground-borne vibration from trains, the crest factor is usually 4 to 5.

non-linearity of human hearing, which causes sounds dominated by low-frequency components to seem louder than broadband sounds that have the same A-weighted level. The result is that a ground-borne noise level of 40 dBA sounds louder than 40 dBA broadband airborne noise. This anomaly is accounted for by setting the limits for ground-borne noise lower than would be the case for broadband noise.

6.2 HUMAN PERCEPTION OF GROUND-BORNE VIBRATION AND NOISE

This section gives some general background on human response to different levels of building vibration, thereby establishing the basis for the criteria for ground-borne vibration and noise that are presented in Chapter 7.

6.2.1 Typical Levels of Ground-Borne Vibration and Noise

In contrast to airborne noise, ground-borne vibration is not a phenomenon that most people experience every day. The background vibration velocity level in residential areas is usually 50 VdB or lower, well below the threshold of perception for humans, which is around 65 VdB. Most perceptible indoor vibration is caused by sources within buildings such as operation of mechanical equipment, movement of people, or slamming of doors. Typical outdoor sources of perceptible ground-borne vibration are construction equipment, steel-wheeled trains, and traffic on rough roads. If the roadway is smooth, the vibration from traffic is rarely perceptible.

Common vibration sources and the human and structural response to ground-borne vibration are illustrated in Figure 6-3. The range of interest is from approximately 50 VdB to 100 VdB. Background vibration is usually well below the threshold of human perception and is of concern only when the vibration affects very sensitive manufacturing or research equipment, such as electron microscopes and high resolution lithography equipment.

The relationship between ground-borne vibration and ground-borne noise depends on the frequency content of the vibration and the acoustical absorption of the receiving room. The more acoustical absorption in a room, the lower the noise level will be. For a room with average acoustical absorption, the sound pressure level is approximately equal to the average vibration velocity level of the room surfaces.[3] Hence, the A-weighted level of ground-borne noise can be estimated by applying A-weighting to the vibration velocity spectrum. Since the A-weighting at 31.5 Hz is -39.4 dB, if the vibration spectrum peaks at 30 Hz, the A-weighted sound level will be approximately 40 decibels lower than the velocity level. Correspondingly, if the vibration spectrum peaks at 60 Hz, the A-weighted sound level will be about 25 decibels lower than the velocity level.

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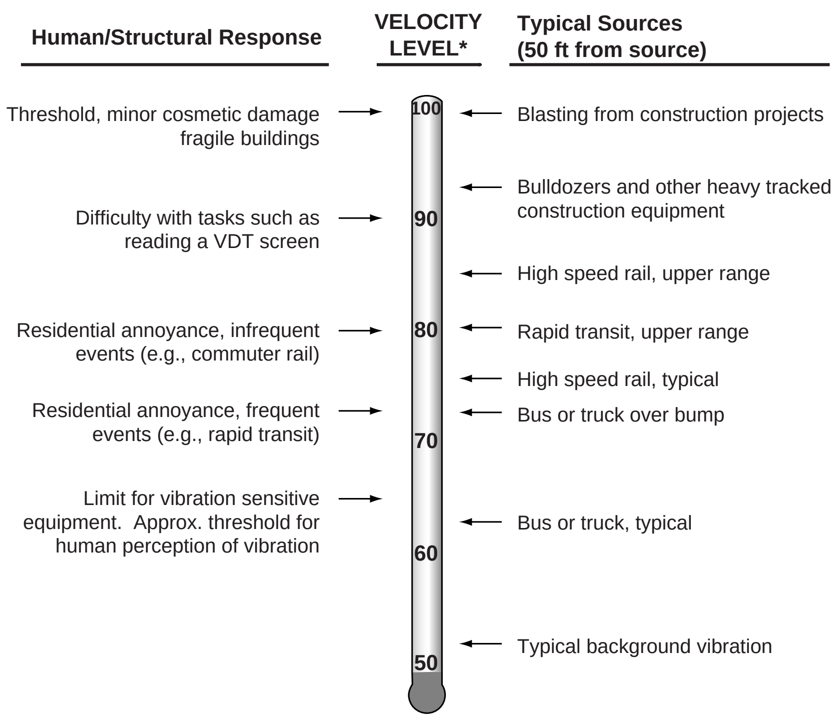
[3] The sound level approximately equals the average vibration velocity level *only* when the velocity level is referenced to 1 micro inch/second. When velocity level is expressed using the international standard of 1×10^{-8} m/sec, the sound level is approximately 8 decibels lower than the average velocity level.

6.2.2 Quantifying Human Response to Ground-Borne Vibration and Noise

One of the major problems in developing suitable criteria for ground-borne vibration is that there has been relatively little research into human response to vibration, in particular, human annoyance with building vibration. However, experience with U.S. rapid transit projects over the past 20 years represents a good foundation for developing suitable limits for residential exposure to ground-borne vibration and noise from high-speed rail operations.



** RMS Vibration Velocity Level in VdB relative to 10^{-6} inches/second*

Figure 6-3 Typical Levels of Ground-Borne Vibration

The relationship between the vibration velocity level measured in 22 homes and the general response of the occupants to vibration from rapid transit trains is illustrated in Figure 6-4. The data points shown were assembled from measurements that had been performed for several transit systems. The subjective ratings are based on the opinion of the person who took the measurements and the response of the occupants. These data were previously published in the "State-of-the-Art Review of Ground-borne Noise and Vibration."[4] Both the occupants and the people who performed the measurements agreed that floor vibration in the "Distinctly Perceptible" category was unacceptable for a residence. The data in Figure 6-4 indicate that residential vibration exceeding 75 VdB is unacceptable if trains are passing every 5 to 15 minutes, as is usually the case with urban transit trains. Additional social survey data is provided by a Japanese study on vibration pollution conducted in 1975.[5] The percent of people annoyed by vibration from high-speed trains in Japan is shown by the “% annoyed” curve in Figure 6-4. Note that the scale corresponding to the percent annoyed is on the right hand axis of the graph. The results of the Japanese study confirm the conclusion that at vibration velocity levels ranging from 75 to 80 VdB, many people will find the vibration annoying.

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[4] J.T. Nelson, H.J. Saurenman, “State-of-the-Art Review: Prediction and Control of Ground-Borne Noise and Vibration from Rail Transit Trains,” U.S. Department of Transportation, Urban Mass Transportation Administration, Report Number UMTA-MA-06-0049-83-4, DOT-TSC-UMTA-83-3, December 1983.

[5] Y. Tokita, “Vibration Pollution Problems in Japan,” In **Inter-Noise 75**, Sendai, Japan, pp. 465-472, 1975.

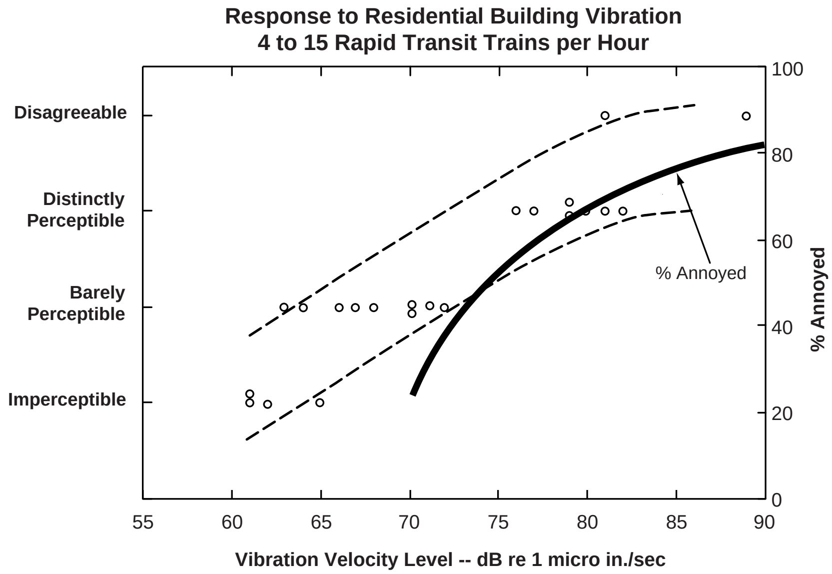


Figure 6-4 Occupant Response to Urban Transit-Induced Residential Vibration

The human response to different levels of ground-borne noise and vibration is described in Table 6-1. The first column lists vibration velocity levels, and the next two columns list the corresponding noise levels assuming that the vibration spectrum peaks at either 30 Hz or 60 Hz. As discussed above, the A-weighted noise level will be approximately 40 dB less than the vibration velocity level if the spectrum peak is around 30 Hz, and 25 dB lower if the spectrum peak is around 60 Hz. However, human response measures illustrate that achieving either the acceptable vibration or acceptable noise levels does not guarantee that the other will be acceptable. The noise caused by vibrating structural components may be very annoying even though the vibration cannot be felt, or the other way around.

Table 6-1 Human Response to Different Levels of Ground-Borne Noise and Vibration

RMS Vibration Velocity Level	Noise Level		Human Response
	Low Freq[1]	Mid Freq[2]	
65 VdB	25 dBA	40 dBA	Approximate threshold of perception for many humans. Low-frequency sound usually inaudible, mid-frequency sound excessive for quiet sleeping areas.
75 VdB	35 dBA	50 dBA	Approximate dividing line between barely perceptible and distinctly perceptible. Many people find train vibration at this level unacceptable. Low-frequency noise acceptable for sleeping areas, mid-frequency noise annoying in most quiet occupied areas.
85 VdB	45 dBA	60 dBA	Vibration acceptable only if there are an infrequent number of events per day. Low-frequency noise unacceptable for sleeping areas, mid-frequency noise unacceptable even for infrequent events with institutional land uses such as schools and churches.

Notes:
1. Approximate noise level when vibration spectrum peak is near 30 Hz.
2. Approximate noise level when vibration spectrum peak is near 60 Hz.

6.3 FACTORS THAT INFLUENCE GROUND-BORNE VIBRATION AND NOISE

Developing accurate estimates of ground-borne vibration is complicated by the many factors that can influence vibration levels at the receiver position. Factors that have significant effects on the levels of ground-borne vibration are discussed in this section. Some of these factors that are known to have, or are suspected of having, a significant influence on the levels of ground-borne vibration and noise are summarized in Table 6-2. As the table indicates, the physical parameters of the track, trainsets, geology, and receiving building all influence vibration levels. The important physical parameters can be divided into the following four categories:

Operational and Vehicle Factors: This category includes all of the parameters that relate to rail vehicles and the operation of trains. Factors such as high speed, stiff primary suspensions on the vehicle, and flat or worn wheels will increase the possibility of ground-borne vibration problems.

Guideway: The type and condition of the rails, the type of guideway, the rail support system, and the mass and stiffness of the guideway structure can all influence the level of ground-borne vibration. Worn rail and wheel impacts at special trackwork can substantially increase ground-borne vibration. A high-speed rail system guideway will be either in tunnel, open trench, at-grade, or aerial viaduct. It is rare for ground-borne vibration to be a problem with aerial railways, except when guideway supports are located within 50 feet of buildings. Directly radiated airborne noise is usually the dominant problem from guideways at-grade or in cut, although vibration can sometimes be a problem. For tunnels that are under residential areas, however, ground-borne noise and vibration are often among the most significant environmental problems.

Geology: Soil conditions are known to have a strong influence on the levels of ground-borne vibration. Among the most important factors are the stiffness and internal damping of the soil and the depth to bedrock. Experience has shown that vibration propagation is more efficient in clay soils as well as areas with shallow bedrock; the latter condition seems to channel or concentrate the vibration energy close to the surface, resulting in ground-borne vibration problems at large distances from the track. Factors such as layering of the soil and depth to water table can also have significant effects on the propagation of ground-borne vibration.

Receiving Building: Ground-borne vibration problems occur almost exclusively inside buildings. Therefore, the characteristics of the receiving building are a key component in the evaluation of ground-borne vibration. The train vibration may be perceptible to people who are outdoors, but it is very rare for outdoor vibration to cause complaints. The vibration levels inside a building depend on the vibration energy that reaches the building foundation, the coupling of the building foundation to the soil, and the propagation of the vibration through the building structure. The general guideline is that the more massive a building is, the lower its response to incident vibration energy in the ground.

Table 6-2 Factors that Influence Levels of Ground-Borne Vibration and Noise

Factors Related to Vibration Source	
Factors	**Influence**
Vehicle Suspension	If the suspension is stiff in the vertical direction, the effective vibration forces will be higher. On transit cars, only the primary suspension affects the vibration levels, the secondary suspension that supports the car body has no apparent effect. Similar effects are likely to occur with high-speed trainsets.
Wheel Condition	Wheel roughness and flat spots are the major cause of vibration from steel-wheel/steel-rail train systems.
Track Surface	Rough track is often the cause of vibration problems. Maintaining a smooth track surface will reduce vibration levels.
Track Support System	On rail systems, the track support system is one of the major components in determining the levels of ground-borne vibration. The highest vibration levels are created by track that is rigidly attached to a concrete trackbed. The vibration levels are much lower when special vibration control track systems such as resilient fasteners, ballast mats, and floating slabs are used.
Speed	As intuitively expected, higher speeds result in higher vibration levels. Doubling speed usually results in vibration levels 4 to 6 decibels higher.
Track Structure	The general rule-of-thumb is that the heavier the track structure, the lower the vibration levels. The vibration levels from a lightweight bored tunnel will usually be higher than from a poured concrete box tunnel.
Depth of Vibration Source	There are significant differences in the vibration characteristics when the source is underground compared to at the ground surface.
Factors Related to Vibration Path	
Factor	**Influence**
Soil Type	It is generally expected that vibration levels will be higher in stiff clay type soils than in loose sandy soils.
Rock Layers	Vibration levels often seem to be high near at-grade track when the depth to bedrock is 30 feet or less. Tunnels founded in rock will result in lower vibration amplitudes close to the tunnel. Because of efficient propagation, the vibration level does not attenuate as rapidly in rock as it does in soil.
Soil Layering	Soil layering will have a substantial, but unpredictable, effect on the vibration levels since each stratum can have significantly different dynamic characteristics.
Depth to Water Table	The presence of the water table is often expected to have a significant effect on ground-borne vibration, but evidence to date cannot be expressed with a definite relationship.
Frost Depth	There is some indication that vibration propagation is more efficient when the ground is frozen.
Factors Related to Vibration Receiver	
Factor	**Influence**
Foundation Type	The general rule-of-thumb is that the heavier the building foundation, the greater the coupling loss as the vibration propagates from the ground into the building.
Building Construction	Since ground-borne vibration and noise almost always are evaluated in terms of indoor receivers, the propagation of the vibration through the building must be considered. Each building has different characteristics relative to structure-borne vibration, although the general rule-of-thumb is that the more massive a building is, the lower the levels of ground-borne vibration will be.
Acoustical Absorption	The amount of acoustical absorption in the receiver room affects the levels of ground-borne noise.

6.4 GROUND-BORNE VIBRATION FROM HIGH-SPEED RAIL SYSTEMS

Available data on ground-borne vibration from high-speed rail systems is primarily from measurements of revenue service operations of the X2000 in Sweden, the Pendolino in Italy, and the TGV and Eurostar trains in France. These data were obtained in May 1995 as part of the data collection task involved in preparing this manual. Vibration measurements were made at two sites in each country, with vibration propagation testing done at the primary site in each country. This measurement program represents one of the first times that detailed ground-borne vibration testing has been carried out in several different countries for high-speed trains operating under normal revenue conditions.

One of the major problems in characterizing ground-borne vibration from trains is that geology has a major influence in vibration levels, and there are no analytical methods of factoring out the effects of geology. This makes it very difficult to compare the levels of ground-borne vibration from different types of trains, unless they are operating on the same track. An experimental method of characterizing vibration propagation characteristics at a specific site that was developed to work around this problem[6] was applied during the tests in Sweden, Italy, and France.

This propagation test procedure basically consists of dropping a weight on the ground and measuring the force of the impact and the vibration pulses at various distances from the impact point. The transfer functions between the vibration pulses and the force impulse are then used to characterize vibration propagation. Assuming a reasonably linear system, these transfer functions define the relationship between any type of exciting force and the resulting ground vibration.

The end result of the propagation test is a measure of the transmissibility of ground vibration, or line source transfer mobility, as a function of distance from the train. Measurements of train vibration and line source transfer mobility at the same site can be used to derive a "force density" function that characterizes the vibration forces of a train independent of the geologic conditions at the site. The test is discussed in greater detail in Chapter 9.

6.4.1 Analysis Procedures

The steps used to analyze the train vibration and ground transfer mobility data to derive force densities were as follows:

1. Transfer mobility and train vibration were expressed in terms of frequency-dependent representations, or frequency spectra.
2. Raw transfer mobility data for *point sources* were combined to approximate *line source* transfer mobility at each test site.

[6]U.S. Department of Transportation, Federal Transit Administration, Transit Noise and Vibration Impact Assessment, “Chapter 11: Detailed Vibration Analysis,” Report DOT-T-95-16, April 1995.

3. Best-fit curves of level vs. distance for each frequency band were obtained using linear regression or other curve-fitting technique, approximate line-source transfer mobility, and train vibration spectra as a function of distance from the source.

4. The difference between the train vibration spectrum and the transfer mobility spectrum at the same distance, or the *force density* spectrum, was calculated. Theoretically the force density should be independent of distance. In practice, however, force density is calculated at each measurement distance, and the average force density is used to characterize each type of trainset. For all of the trainsets, the force densities at the six measurement distances converged to within 3 to 4 decibels of the average.

6.4.2 Trainset Vibration Measurement Results

Vibration velocity measurement results for several different types of high-speed trains are shown in Figure 6-5. Included in Figure 6-5 are results from: 1) the European measurements in May 1995; 2) tests with X2000 equipment on the Northeast Corridor; and 3) measurements of TGV trains in 1991. All of the data points have been normalized to 150 mph. The wide spread in the data is partly due to differences in the equipment and track condition, and partly from differences in geology. To clarify the trends, Figure 6-6 shows best-fit curves for the same data.

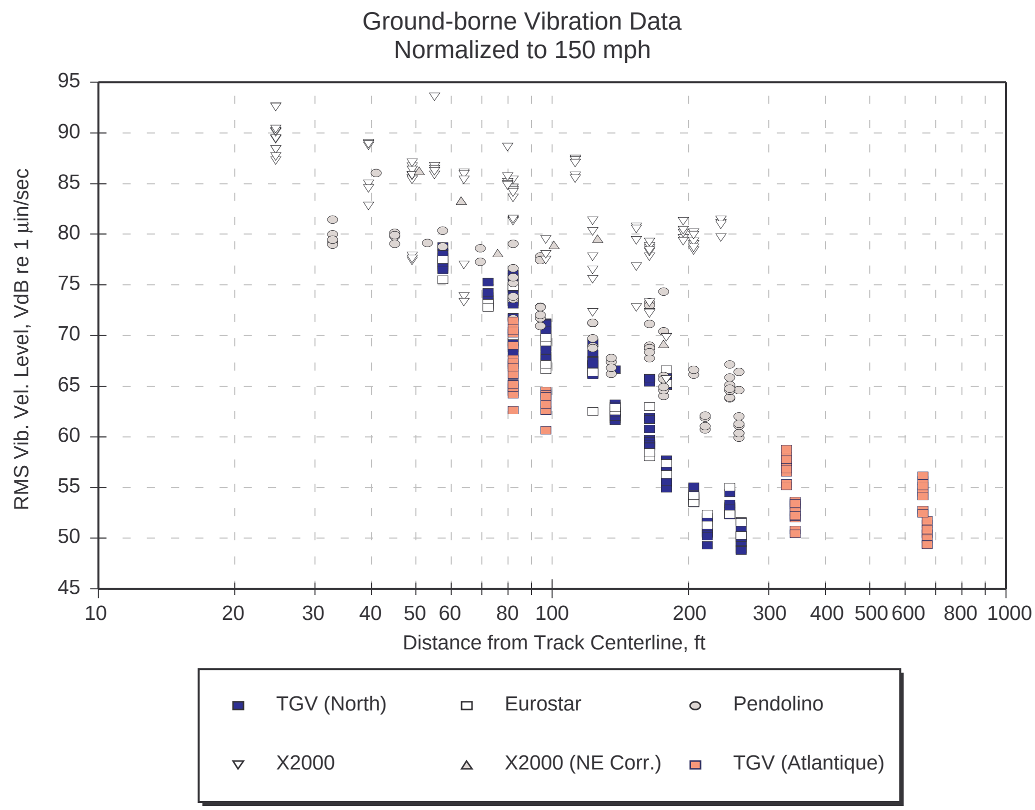


Figure 6-5 Overall Vibration Velocity Level for Different High Speed Trains

Some observations derived from the measurements presented in Figures 6-5 and 6-6 are:

- The TGV and Eurostar trainsets measured along the Nord (North) line in France all had very similar vibration levels. The TGV data measured on the Atlantique line show a distinctly different characteristic.
- The Pendolino trainsets measured in Italy have vibration levels similar to the TGV trainsets operating on the Nord line.
- The X2000 trainsets measured in Sweden show vibration levels much higher than those of the TGV or Pendolino trainsets. However, as discussed later, normalizing the data to a single set of soil conditions indicate that X2000 trainsets actually generate ground-borne vibration forces similar to the other high-speed trains. Consequently, the higher levels appear to be primarily due to the propagation conditions of the ground at the test site in Sweden.
- The test with the X2000 trainset on the Northeast Corridor show relatively high vibration levels. Because propagation tests were not a part of the Northeast Corridor testing, however, it is unknown whether these higher vibration levels were due to geology, track condition, wheel condition, or other factors.

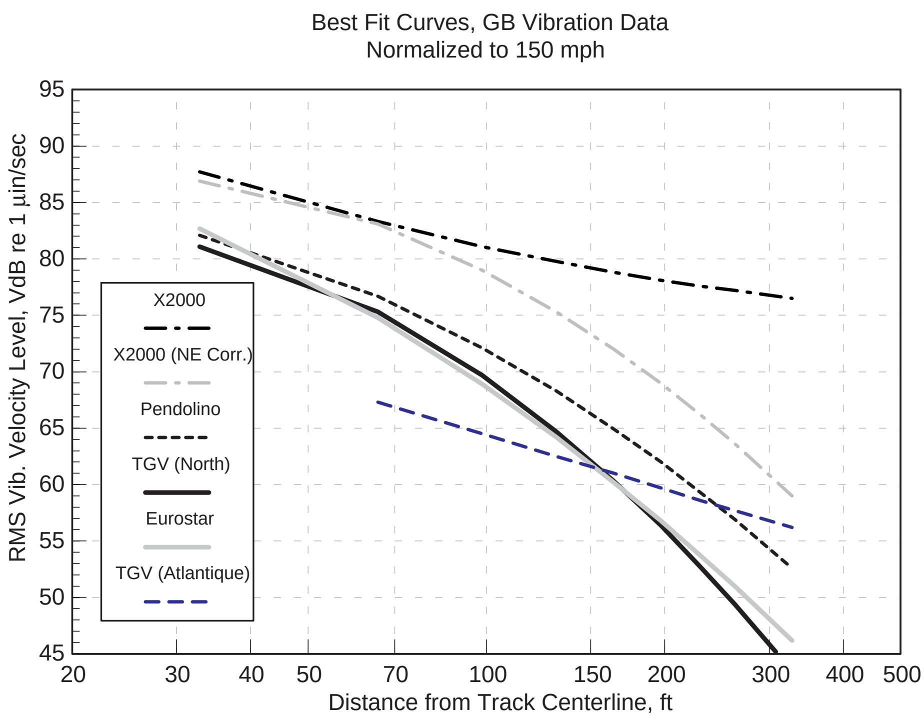


Figure 6-6 Best-Fit Curves of Vibration Velocity Level vs. Distance

A summary of the overall vibration velocity levels of the trainsets measured in Europe, calculated from the smoothed 1/3 octave band spectra, are shown in Figure 6-7. The differences in the vibration levels measured with the different types of trainsets are shown clearly. The X2000 had significantly higher vibration at all distances, with the levels over 30 decibels higher than the TGV trainsets at 100 meters from the tracks.

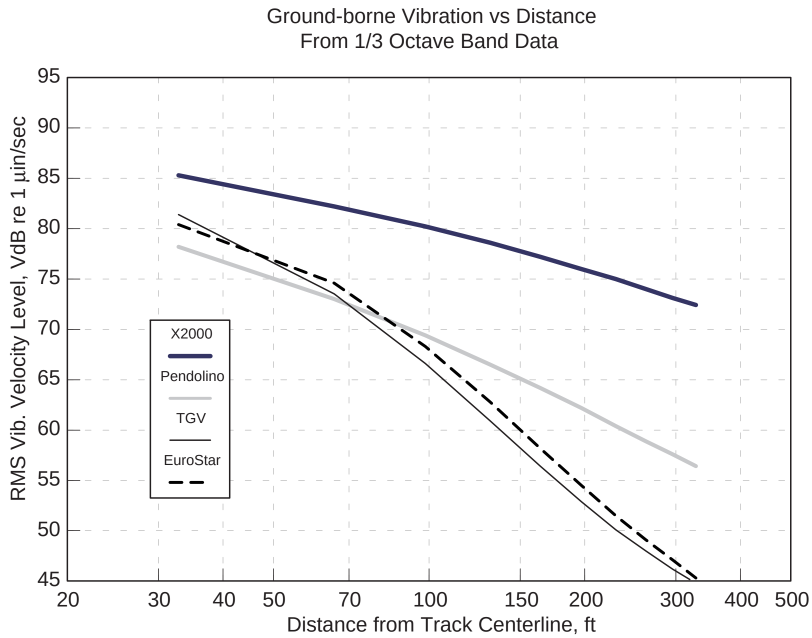


Figure 6-7 Vibration Velocity vs. Distance Calculated from Smoothed 1/3 Octave Bands

Figures 6-5, 6-6, and 6-7 indicate the overall levels of ground-borne vibration as a function of distance, but do not indicate the dominant frequency range in the ground-borne vibration generated by each trainset. Knowing the dominant frequency range helps determine whether the ground-borne vibration is perceived as vibration or audible noise by occupants of buildings near train tracks. The measured vibration velocity in terms of 1/3 octave band levels for the TGV, X2000, and Pendolino trainsets normalized to 150 mph are shown in Figure 6-8. The X2000 measured at the test site in Sweden showed the highest levels of low-frequency vibration below 40 Hz, with the Pendolino data falling between the X2000 and the TGV in this range. In fact, the X2000 vibration levels were higher over the entire frequency spectrum, except at 50 and 63 Hz, where TGV vibration was highest.

As discussed above, much of the difference between the trainsets is likely to be due to geology variations rather than differences in suspension, axle load or wheel conditions of the trainsets. The line source transfer mobility spectra, which indicate the frequency-dependent response characteristics of the ground, for the three different measurement sites are shown in Figure 6-9. It is clear that the transfer mobilities are very different between the three primary sites in France, Italy and Sweden. For example, at 100 Hz the transfer mobility measured at the site in Sweden is 8 decibels higher than the site in France and about 30 decibels higher than the site in Italy. All of the sites were in rural areas where relatively little is known about the specific geology at the test sites. The measurements indicated that these differences in transfer mobility are fairly consistent out to 100 meters from the vibration source.

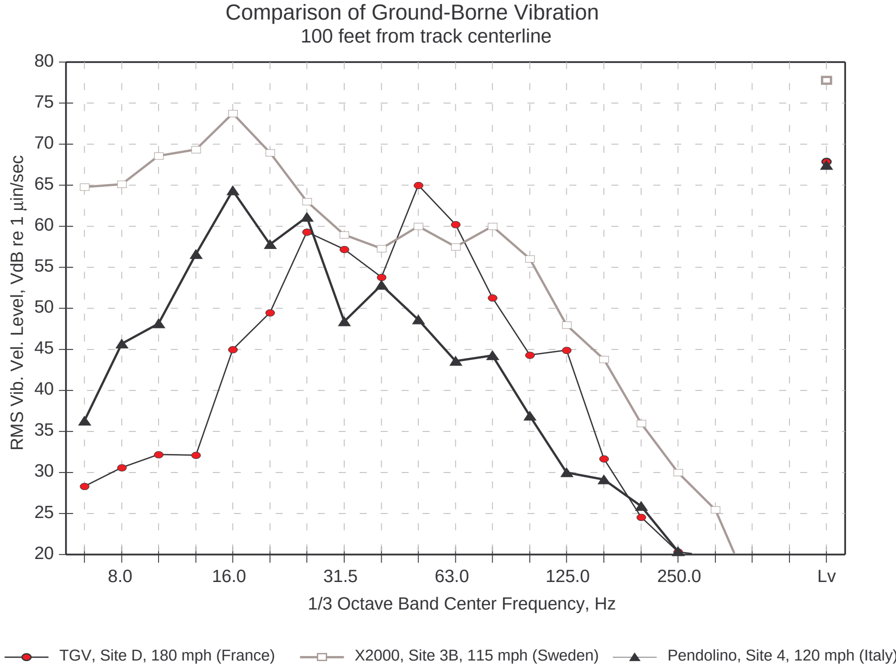


Figure 6-8 Comparison of 1/3 Octave Band Spectra

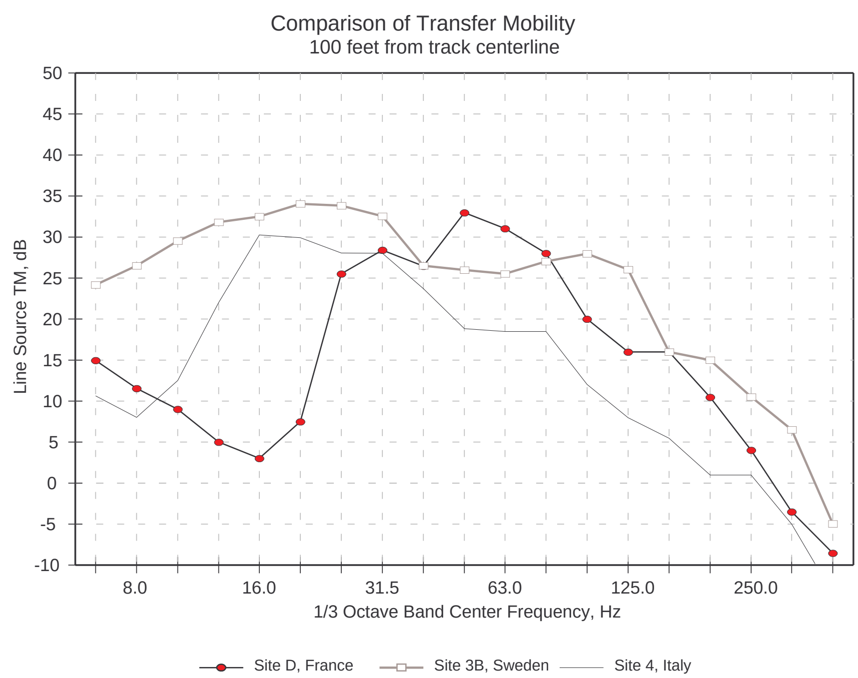


Figure 6-9 Line-Source Transfer Mobility at the Test Sites

The force density functions derived for X2000, Pendolino, TGV, and Eurostar trainsets, all normalized to a speed of 150 mph, are shown in Figure 6-10. The force densities are also very different, but the differences are not as large as the measured ground vibration levels. The TGV and Eurostar force densities are close enough to be considered the same. The X2000 and the Pendolino are surprisingly similar, considering the large difference in the vibration spectra.

The four force density functions can each be combined with the transfer mobility from a single site to approximate what the vibration levels would be if all of the trainsets were operating on the same track at the same location. The resulting overall vibration levels using the transfer mobility from the primary site (Site D) in France are shown in Figure 6-11, and the same results using the transfer mobility from the primary site (Site 3B) in Sweden are shown in Figure 6-12.

Both figures show that using the same transfer mobility, in effect normalizing the ground vibration from the trainsets to one site, substantially reduces the differences in the overall vibration levels. Using the transfer mobility from Sweden, the TGV, Eurostar, and X2000 are all within about 2 decibels, and the Pendolino is 3 to 4 decibels lower. In this case, the range of ground-borne vibration from the different trainsets is limited to a narrow "band" between 75 and 80 VdB at 30 meters from the track. Using the transfer mobility from France, the TGV and Eurostar are 2 to 3 decibels lower than the Pendolino, and the X2000 is about 4 decibels higher than the Pendolino. The levels range from 65 to 73 VdB at 30 meters from the track centerline. The overall conclusion drawn is that all of the trainsets would generate significantly higher ground vibration levels at the Swedish test site than at the French site.

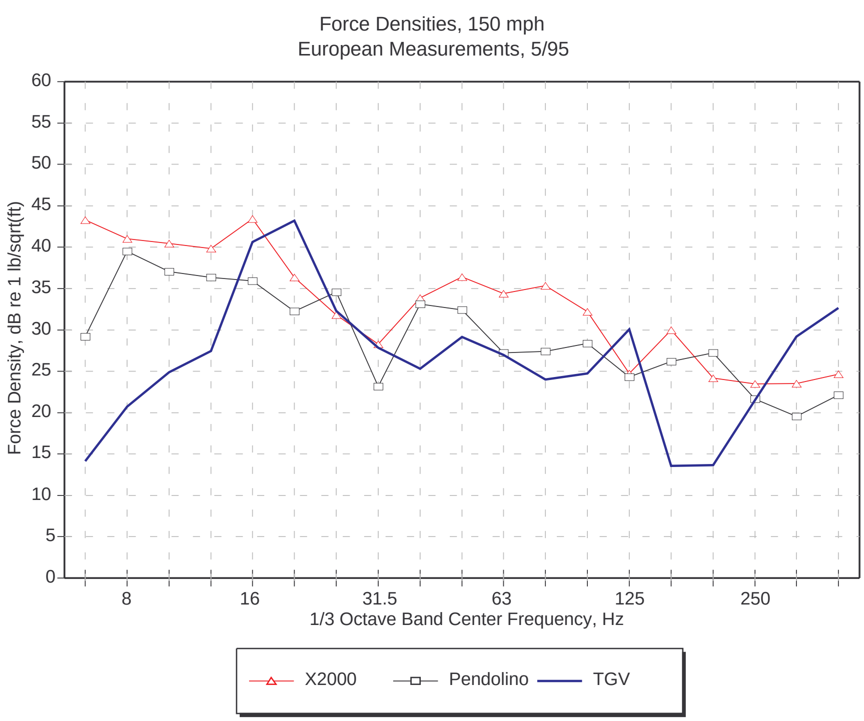
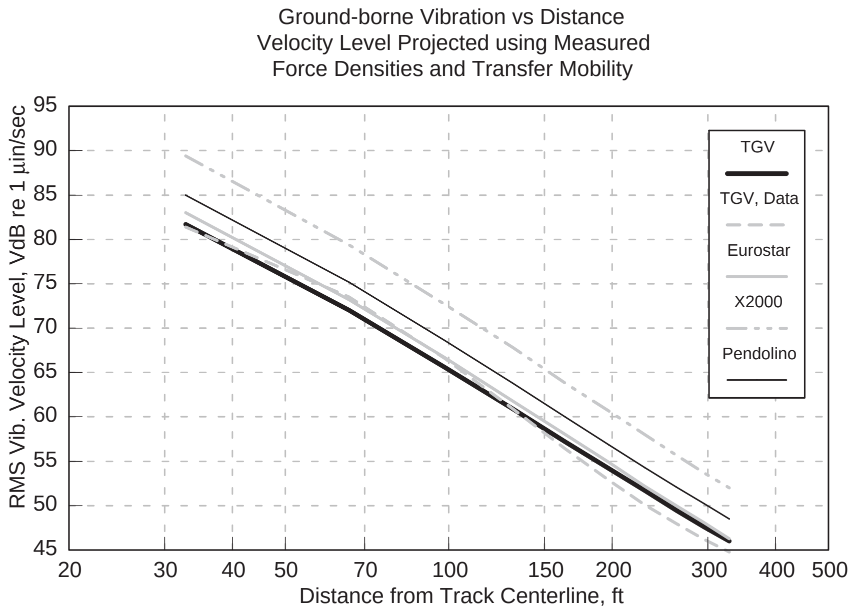
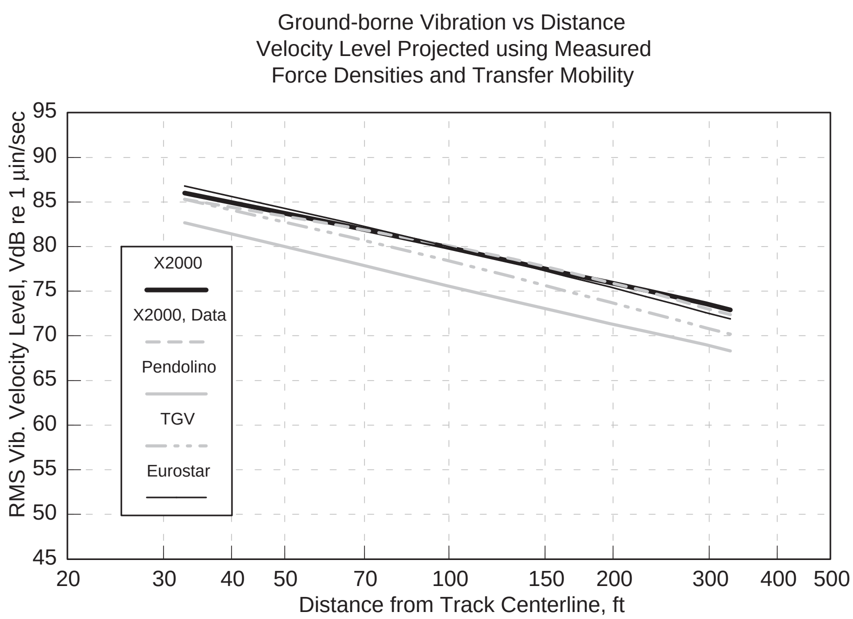


Figure 6-10 Force Density Functions Derived from Measurements



Using transfer mobility from
Site D in France
Train Speed 150 mph

Figure 6-11 Projected Vibration Velocity, Transfer Mobility from Site in France



Using transfer mobility from
Site 3B in Sweden
Train Speed 150 mph

Figure 6-12 Projected Vibration Velocity, Transfer Mobility from Site in Sweden

Finally, to further illustrate the strong effects of the transfer mobility, the results of applying the X2000 force density to the transfer mobility functions at each of the three primary sites are shown in Figure 6-13, in terms of overall vibration level as a function of distance. This shows that close to the track centerline, the projected vibration levels are all relatively high. However, the levels with the transfer mobility from Site 3B in Sweden show considerably slower attenuation with distance than with the other two transfer mobilities due to geological factors.

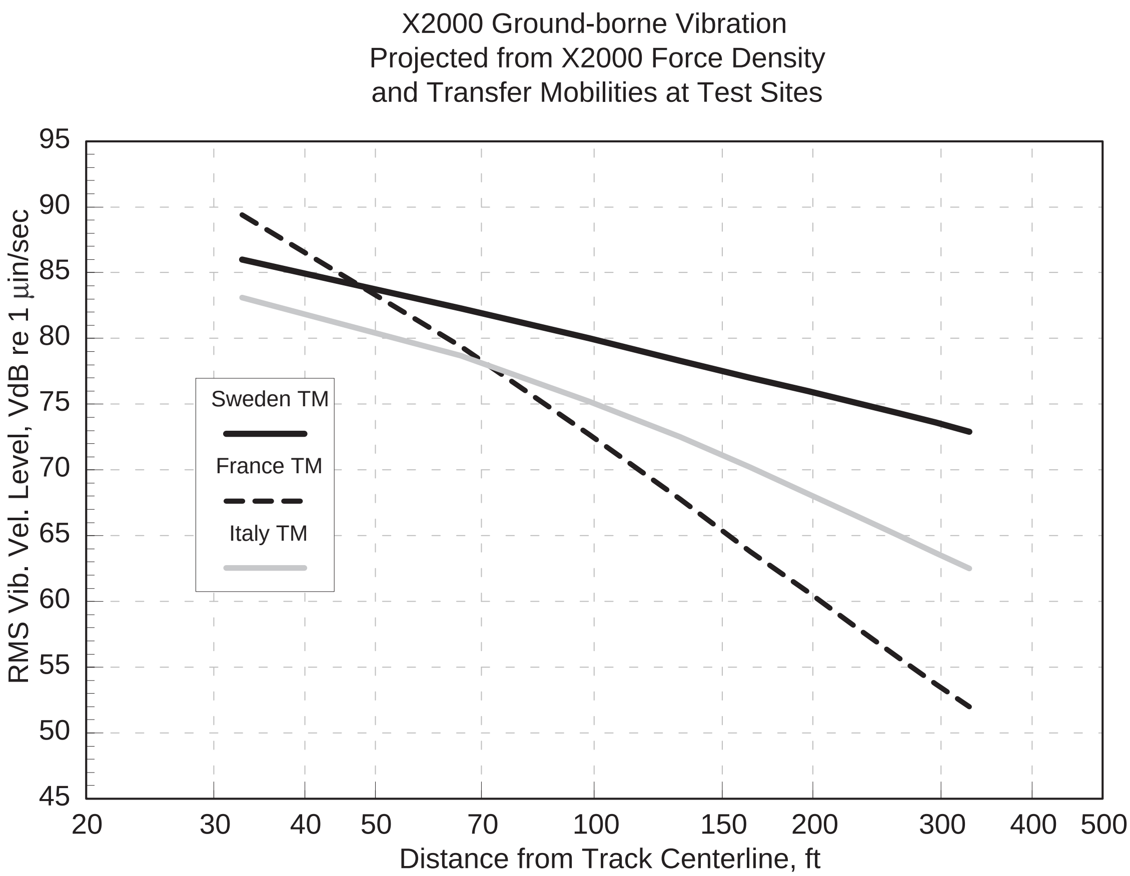


Figure 6-13 Projected Vibration Velocity, X2000 Force Density

Chapter 7

VIBRATION IMPACT CRITERIA

The environmental impacts of vibration from high-speed trains are similar to those of other types of trains. The resulting building vibration can be perceptible and intrusive to building occupants and can cause secondary rattling of windows, items on shelves, and pictures hanging on walls. In addition, the sound reradiated from vibrating room surfaces, referred to as ground-borne noise, often will be audible in the form of a low-frequency rumbling sound.

Because of the relatively rare occurrence of annoyance due to ground-borne vibration and noise, there has been only limited sponsored research of human response to building vibration and structure-borne noise. However, with the construction of new rail rapid transit systems in the past 20 years, considerable knowledge has been gained as to how communities will react to various levels of building vibration. This experience, combined with the available national and international standards,[1,2] represents a good foundation for predicting annoyance from ground-borne noise and vibration in residential areas that would be caused by a high-speed rail project. The criteria for ground-borne vibration and noise included in this chapter are based on the FTA manual *Transit Noise and Vibration Impact Assessment*[3] with only minor modifications.

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[1]Acoustical Society of America, "American National Standard: Guide to Evaluation of Human Exposure to Vibration in Buildings," ANSI S3.29-1983 (ASA 48-1983).

[2]International Standards Organization, "Evaluation of Human Exposure to Whole-Body Vibration, Part 2: Continuous and Shock-Induced Vibrations in Buildings (1-80Hz)," ISO-2361-2, 1989.

[3]U.S. Department of Transportation, Federal Transit Administration, *Transit Noise and Vibration Impact Assessment*, Report Number DOT-T-95-16, April 1995.

The criteria for environmental impact from ground-borne vibration and noise presented in Table 7-1 are based on the maximum levels for a single event. The criteria account for variation in land use as well as the frequency of events, which can differ widely among high-speed rail projects. Most experience is with the community response to ground-borne vibration from rail rapid transit systems with typical headways in the range of 3 to 10 minutes and each vibration event lasting less than 10 seconds. Intuition suggests that with many fewer events each day, as is typical for high-speed rail projects, it should take higher vibration levels to evoke the same community response. Consequently, the criteria distinguish between projects with frequent and infrequent events, where *Frequent Events* are defined as more than 70 events per day. The dividing line between frequent and infrequent events was originally selected in the FTA manual such that most commuter rail projects fall into the infrequent event category. Intercity rail operations are assumed to fall into the infrequent category.

Table 7-1 Ground-Borne Vibration and Noise Impact Criteria

Land Use Category	Ground-Borne Vibration Impact Levels (VdB re 1 micro inch/sec)		Ground-Borne Noise Impact Levels (dB re 20 micro Pascals)	
	Frequent[1] Events	Infrequent[2] Events	Frequent[1] Events	Infrequent[2] Events
Category 1: Buildings where vibration would interfere with interior operations.	65 VdB[3]	65 VdB[3]	N/A[4]	N/A[4]
Category 2: Residences and buildings where people normally sleep.	72 VdB	80 VdB	35 dBA	43 dBA
Category 3: Institutional land uses with primarily daytime use.	75 VdB	83 VdB	40 dBA	48 dBA

Notes:
1. *Frequent Events* is defined as more than 70 vibration events per day.
2. *Infrequent Events* is defined as fewer than 70 vibration events per day.
3. This criterion limit is based on levels that are acceptable for most moderately sensitive equipment such as optical microscopes. Vibration-sensitive manufacturing or research will require detailed evaluation to define the acceptable vibration levels. Ensuring lower vibration levels in a building often requires special design of the HVAC systems and stiffened floors.
4. Vibration-sensitive equipment is not sensitive to ground-borne noise.

The criteria are based primarily on experience with passenger train operations, with only limited experience from freight train operations. The difference is that passenger train operations, whether rapid transit, commuter rail, normal, or high-speed intercity, create vibration events that last less than about 10 seconds. A typical line-haul freight train is about 5,000 feet long. At a speed of 30 mph, it takes a 5,000-foot freight train approximately two minutes to pass. Even though the criteria are primarily based on experience with shorter vibration events and this manual is oriented to high-speed rail projects, in some situations potential impacts from freight train ground-borne vibration may need to be evaluated. The prime example is the operation of high-speed trains within an existing freight railroad right-of-way. Some guidelines for applying these criteria to rail corridors with existing freight or passenger trains are given later in this chapter.

The criteria for acceptable ground-borne vibration are expressed in terms of RMS velocity levels in decibels. The criteria for acceptable ground-borne noise are expressed in terms of A-weighted sound level. The limits are specified for the three land-use categories defined below:

Vibration Category 1: High Sensitivity – Category 1 includes buildings where it is essential that ambient vibrations be kept very low for the operations within the building. Vibration levels in this category may be well below levels associated with human annoyance. (Concert halls and other special use facilities are covered separately in Table 7-2.) Typical land uses covered by Category 1 are vibration-sensitive research and manufacturing facilities, hospitals with vibration-sensitive equipment, and university research operations. The degree of sensitivity to vibration will depend on the specific equipment that will be affected by the vibration. Equipment such as electron microscopes and high-resolution lithographic equipment can be very sensitive to vibration, and even normal optical microscopes will sometimes be difficult to use when vibration is well below the human annoyance level. Manufacturing of computer chips is an example of a vibration-sensitive process.

The vibration limits for Vibration Category 1 are based on acceptable vibration for moderately vibration-sensitive equipment, such as optical microscopes and electron microscopes with vibration isolation systems. Defining limits for equipment that is even more sensitive requires a detailed review of the specific equipment involved. This type of review is usually performed during the final design phase and not as part of the environmental impact assessment. Mitigation of train vibration that affects sensitive equipment typically involves modification of the equipment mounting system or relocation of the equipment rather than applying vibration control measures to the high-speed rail project.

This category does not include most computer installations or telephone switching equipment. Although the owners of this type of equipment often are very concerned about the potential of ground-borne vibration interrupting smooth operation of their equipment, computers and other electronic equipment are rarely sensitive to vibration. Most such equipment is designed to operate in typical building environments where it may experience occasional shock from bumping and continuous background vibration caused by other equipment.

Vibration Category 2: Residential – This category covers all residential land uses and any buildings where people sleep, such as hotels and hospitals. No differentiation is made between different types of residential areas. This equal consideration is given primarily because ground-borne vibration and noise are experienced indoors, and building occupants have practically no means to reduce their exposure. Even in a noisy urban area, bedrooms often will be quiet in buildings that have effective noise insulation and tightly closed windows. Hence, an occupant of a bedroom in a noisy urban area is likely to be just as sensitive to ground-borne noise and vibration as someone in a quiet suburban area.

Vibration Category 3: Institutional – Vibration Category 3 includes schools, churches, other institutions, and quiet offices that do not have vibration-sensitive equipment, but still have the potential for activity interference. Although it is generally appropriate to include office buildings in this category, it is not appropriate to include all buildings that have any office space. For example, most industrial buildings have office space, but buildings primarily for industrial use are not intended to be included in this category.

Some buildings, such as concert halls, television and recording studios, and theaters, can be very sensitive to vibration and noise but do not fit into any of the three categories. Because of the sensitivity of these buildings, they usually warrant special attention during the environmental assessment of a high-speed rail project. Criteria for acceptable levels of ground-borne vibration and noise for various types of special buildings are given in Table 7-2.

Table 7-2 Ground-Borne Vibration and Noise Impact Criteria for Special Buildings

Type of Building or Room	Ground-Borne Vibration Impact Levels (VdB re 1 micro-inch/sec)		Ground-Borne Noise Impact Levels (dB re 20 micro-Pascals)	
	Frequent[1] Events	Infrequent[2] Events	Frequent[1] Events	Infrequent[2] Events
Concert Halls	65 VdB	65 VdB	25 dBA	25 dBA
TV Studios	65 VdB	65 VdB	25 dBA	25 dBA
Recording Studios	65 VdB	65 VdB	25 dBA	25 dBA
Auditoriums	72 VdB	80 VdB	30 dBA	38 dBA
Theaters	72 VdB	80 VdB	35 dBA	43 dBA

Notes:
1. *Frequent Events* is defined as more than 70 vibration events per day.
2. *Infrequent Events* is defined as fewer than 70 vibration events per day.

The criteria related to ground-borne vibration causing human annoyance or interfering with use of vibration-sensitive equipment are listed in Tables 7-1 and 7-2. It is extremely rare for vibration from train operations to cause any sort of building damage, even minor cosmetic damage. However, there is sometimes concern about damage to fragile historic buildings located near the right-of-way. Even in these cases, damage is unlikely except when the track will be very close to the structure. Damage thresholds that apply to these structures are discussed in Chapter 10.

In most cases, except near railroad tracks, the existing environment does not include a significant number of perceptible ground-borne vibration or noise events. However, it is common for high-speed rail projects to use parts of existing rail corridors. The criteria given in Tables 7-1 and 7-2 do not indicate how to account for existing vibration, a common situation for high-speed rail projects using existing rail right-of-ways. Methods of handling representative scenarios include the following:

1. <u>Infrequently used rail corridor</u>: Use the vibration criteria from Tables 7-1 and 7-2 when the existing rail traffic consists of at most one or two trains per day.
2. <u>Moderately used rail corridor</u>: If the existing traffic consists of more than about 10 trains per day with vibration that substantially exceeds the impact criteria, there is no impact as long as the project

vibration levels estimated using the procedures outlined in either Chapter 8 or 9 are at least 5 to 10 decibels less than the existing vibration. Vibration from existing trains could be estimated using the General Assessment procedures in Chapter 8; however, it is usually preferable to measure vibration from existing train traffic.

3. Heavily used rail corridor: If the project will not significantly increase the number of vibration events (less than doubling the number of trains is usually considered not significant), there will not be additional impact unless the project vibration, estimated using the procedures of Chapters 8 or 9, will be higher than the existing vibration. In locations where the new trains will be operating at much higher speeds than the existing rail traffic, it is likely that the high-speed trains will generate substantially higher levels of ground-borne vibration. When the project will cause vibration higher than the existing source, the existing source can be ignored and the vibration criteria in Tables 7-1 and 7-2 applied to the project.

4. Moving existing tracks: Another scenario where existing vibration can be significant is a new high-speed rail line within an existing rail right-of-way that will require shifting the location of existing tracks. Where the track relocation will cause higher vibration levels at sensitive receptors, then the projected vibration levels from both rail systems must be compared to the appropriate impact criterion to determine if there will be impact. Although the impact thresholds given in Tables 7-1 and 7-2 are based on experience with vibration from rail transit systems, they can be applied to freight train vibrations as well. However, locomotive and rail car vibration should be considered separately. Because the locomotive vibration only lasts for a few seconds, the infrequent event limit is appropriate, but for a typical line-haul freight train where the rail car vibration lasts for several minutes, the frequent-event limits should be applied to the rail car vibration. Some judgment must be exercised to make sure that the approach is reasonable. For example, some spur rail lines carry very little rail traffic (sometimes only one train per week) or have short trains, in which case the infrequent limits are appropriate.

Chapter 8

PRELIMINARY VIBRATION ASSESSMENT

Procedures that can be used to develop generalized predictions of ground-borne vibration and noise are described in this chapter. There are three different levels of detail for projecting ground-borne vibration:

Screening – The screening procedure uses a table of distances to determine whether noise-sensitive land uses are close enough to the proposed high-speed rail system for impact from ground-borne vibration to be possible. More detailed analysis is required if any sensitive land uses are within the screening distances. The screening procedure does not require any specific knowledge about the vibration characteristics of the system or the geology of the area.

General Assessment – The general level of assessment uses generalized data to develop a curve of vibration level as a function of distance from the track. The vibration levels at specific buildings are estimated by reading values from the curve and applying adjustments to account for factors such as track support system, train speed, track and wheel condition, type of building, and receiver location within the building. The general level deals only with the overall vibration velocity level and the A-weighted sound level. It does not consider the frequency spectrum of the vibration or noise.

Detailed Analysis – The detailed analysis involves applying all of the available tools for accurately projecting the vibration impact at specific sites. The procedure outlined in this manual includes a test of the trainset (or similar trainset) to define the forces generated by the vibration source and tests at the sites in question to define how the local geology affects vibration propagation. Developing detailed projections of ground-borne vibration is considerably more complex than developing detailed projections of airborne noise. The vibration projection procedure is not only complex, but also has not yet been standardized. Accurate projections of ground-borne vibration require professionals with experience in performing and interpreting vibration propagation tests. As such, detailed vibration predictions are usually performed during the final design phase of a project when there is sufficient reason to suspect adverse vibration impact from the project.

The Screening and General Assessment methods are discussed in this chapter. The Detailed Analysis procedure, which is based on measurements to characterize vibration propagation at specific sites, is presented in Chapter 9.

General and detailed predictions do not always have a clear distinction. For example, it is often appropriate to use several representative measurements of vibration propagation along the planned alignment in developing generalized propagation curves. At other times, generalized prediction curves may be sufficient for most of an alignment, with detailed analysis applied to particularly sensitive buildings, such as a concert hall.

The purpose of the General Assessment is to provide a relatively simple method of developing estimates of the overall levels of ground-borne vibration and noise that can be compared to the acceptability criteria given in Chapter 7. For many projects, particularly when comparing alternatives, this level of detail will be sufficient for the environmental assessment. Where potential problems exist, the Detailed Analysis is then undertaken during final design of the selected alternative to define accurately the level of impact and design mitigation measures. A Detailed Analysis usually will be required when designing special track-support systems, such as floating slabs or ballast mats. Detailed Analysis is not usually required if the mitigation measure consists of relocating a crossover or turnout.

8.1 VIBRATION SCREENING PROCEDURE

The screening method is intended to be applied early in a project development before many details on the system have been defined. It allows a quick check to identify whether and where impacts from ground-borne vibration are likely. Screening distances for three different speed ranges and two general types of land use are given in Table 8-1.

Table 8-1 Screening Distances for Vibration Assessments
(applicable to steel-wheel/steel-rail high-speed rail systems)

Land Use	Train Frequency*	Screening Distance, ft		
		Train Speed		
		Less than 100 mph	100 to 200 mph	up to 300 mph
Residential	Frequent	120	220	275
	Infrequent	60	100	140
Institutional	Frequent	100	160	220
	Infrequent	20	70	100

*Frequent = greater than 70 passbys per day.
Infrequent = less than 70 passbys per day.

The screening distances given in Table 8-1 are based on the criteria presented in Chapter 7 and the Generalized Assessment procedures discussed in Section 8.2, assuming "normal" vibration propagation conditions. "Efficient" vibration propagation conditions, characterized by the transmission of ground vibration at low rates of attenuation with distance, can result in substantially higher vibration levels. Efficient propagation has not been assumed in developing the screening distances, since it is a relatively unusual condition and assuming efficient propagation would overestimate the potential for vibration impact. However, by not accounting for the possibility of efficient vibration propagation, some potential impact areas may not be identified in the screening process. When there is evidence of efficient propagation, such as previous complaints about existing rail facilities or a history of problems with construction vibration, the distances in Table 8-1 should be increased by a factor of 2.

8.2 GENERALIZED VIBRATION ASSESSMENT PROCEDURE

The basic approach of the General Assessment procedure is to use a base curve of overall ground-surface vibration as a function of distance from the source, then to apply adjustments to this curve to account for factors such as track support system, train speed, track and wheel condition, building type, and receiver location within the building. This section only considers steel-wheel/steel-rail technology, which, in terms of ground-borne vibration, is no different from existing intercity passenger train and transit trains. For another type of technology, it will be necessary to define an appropriate curve either by extrapolating from existing information or by performing measurements at an existing facility.

8.2.1 Base Curve

The generalized projection curve for steel-wheeled high-speed trains is shown in Figure 8-1. This curve represents typical ground-surface vibration levels assuming equipment in good condition and speeds of 150 mph. The levels must be adjusted to account for factors such as different speeds, equipment, and geologic conditions than those assumed in the figure. The curve in Figure 8-1 is based on the ground-borne vibration measurement data discussed in Section 6.4.

The curve in Figure 8-1 is applicable to high-speed trains both at-grade and in tunnel. The rationale for applying the same curve to these two very different conditions is based on the analysis done for the FTA manual *Transit Noise and Vibration Impact Assessment*.[1] In developing generalized prediction curves for the FTA manual, investigators found that transit trains operating at grade and in tunnel had similar overall vibration levels. This finding was rather surprising because transit trains operating in tunnels tend to generate more vibration complaints than those operating on at-grade track. This tendency is probably due to two factors: (1) tunnels are usually located close to buildings, often directly under them, in densely developed areas, and (2) for at-grade systems, airborne noise from train passbys is usually more noticeable than the ground-borne vibration generated. Although the overall vibration levels from trains operating in tunnel and above grade are similar, there are differences in the frequency spectra of

[1] U.S. Department of Transportation, Federal Transit Administration, *Transit Noise and Vibration Impact Assessment*, Report Number DOT-T-95-16, April, 1995.

the vibration. The ground-borne vibration from trains in tunnels tends to be higher frequency than the vibration from at-grade track, and higher frequencies make the ground-borne noise from tunnels more noticeable in nearby buildings.

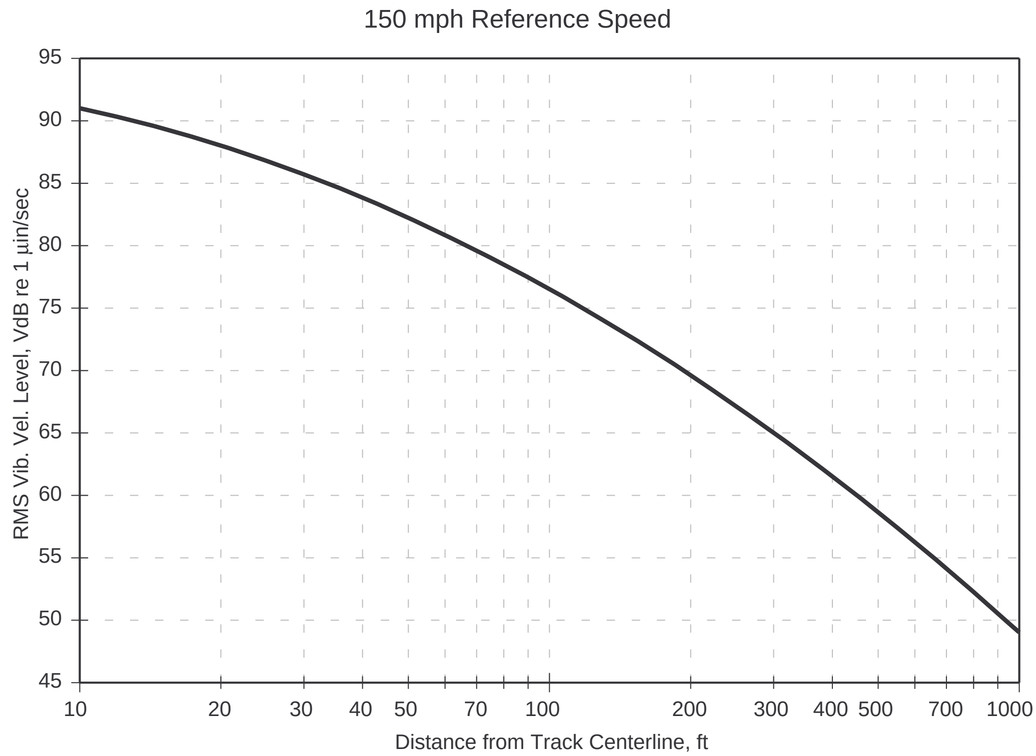

Figure 8-1 Generalized Ground-Borne Vibration Curve

The curve in Figure 8-1 is the same as the curve in the FTA manual (ref. 1) that is applicable to urban transit trains, except that this curve is 10 VdB higher to account for the speed adjustment from 50 mph for urban transit to 150 mph for high-speed rail. This curve represents the high range of the available measurement data of high-speed train ground-borne vibration. Only data from locations known to have unusual vibration propagation conditions were consistently above the curve.

Experience with ground-borne vibration data has shown that, for any specific type of transit mode, a 5 to 10-decibel fluctuation in vibration levels under apparently similar conditions is not uncommon. The curve in Figure 8-1 represents the upper range of the measurement data. Although actual levels fluctuate widely, ground-borne vibration rarely will exceed the curve in Figure 8-1 by more than 1 or 2 decibels unless there are extenuating circumstances, such as rail corrugations, flat spots on wheels, or efficient vibration propagation.

It is not recommended to show projections of normal fluctuation as a "range" of vibration levels. For example, the projected level from Figure 8-1 at a train speed of 150 mph is about 72 VdB, the threshold for acceptable ground-borne vibration for residential land uses, at a distance of 180 feet from the track centerline. If shown as a range to reflect normal fluctuations, the projected level of ground-borne vibration might be given as a range between 67 and to 72 VdB, and the interpretation of whether the projected vibration levels exceed the impact threshold becomes unclear. However, because actual levels of ground-borne vibration will sometimes differ substantially from the projections, some care must be taken when interpreting projections. Some guidelines are given below:

1. Projected vibration is below the impact threshold. Vibration impact is unlikely in this case.
2. Projected ground-borne vibration is 0 to 5 decibels greater than the impact threshold. In this range there is still a significant chance (at least 50 percent) that actual ground-borne vibration levels will be below the impact threshold. In this case, the impact would be reported in the environmental document as exceeding the applicable threshold, and a commitment would be made to conduct more detailed studies to refine the vibration impact analysis and determine appropriate mitigation during final design. A site-specific Detailed Analysis may show that vibration control measures are not needed.
3. Projected ground-borne vibration is 5 decibels or more greater than the impact threshold. Vibration impact is probable and some type of vibration control should be incorporated into the final design of the project.

The two most important factors that must be accounted for in a General Assessment are the type of vibration source and the vibration propagation characteristics. It is well known that there are situations in which ground-borne vibration propagates much more efficiently than normal. The result is unacceptable vibration levels at distances two to three times the normal distance. Unfortunately, the geologic conditions that promote efficient propagation have not been well documented and are not fully understood. Shallow bedrock or clay soils often are involved. One possibility is that shallow bedrock acts to keep the vibration energy near the surface. Much of the energy that would normally radiate down is directed back towards the surface by the rock layer, with the result that the ground surface vibration is higher than normal.

8.2.2 Adjustment Factors

Once the vibration levels have been projected using the base curve in Figure 8-1, the adjustments listed in Table 8-2 can be used to develop vibration projections for specific receiver positions inside buildings. All of the adjustments are given as numbers to be added to, or subtracted from, the base level. The adjustment parameters are speed, wheel and rail type and condition, type of track support system, type of building foundation, and number of floors above the basement level. Many of these adjustments depend heavily on the frequency spectrum of the vibration source and the frequency dependence of the vibration propagation. The single numbers given are suitable for generalized evaluation of the vibration impact and vibration mitigation measures since they are based on typical vibration spectra. However, the general adjustments are not adequate for detailed evaluations of impact of sensitive buildings or for detailed specification of mitigation measures. Careful consideration of the shape of the actual vibration spectra will avoid selection of an inappropriate vibration control measure, which in some cases could actually cause an increase in the vibration levels.

Table 8-2 Adjustment Factors for Generalized Predictions of Ground-Borne Vibration and Noise

Factors Affecting Vibration Source

Source Factor	Adjustment to Propagation Curve		Comment
Speed	Vehicle Speed	Adjustment (Ref Speed = 150 mph)	Vibration level is approximately proportional to 20*log(speed/speed$_{ref}$). Sometimes the variation with speed has been observed to be as low as 10 to 15 log(speed/speed $_{ref}$).
	300 mph	+6.0 dB	
	200 mph	2.5 dB	
	150 mph	0.0 dB	
	100 mph	-3.5 dB	
	75 mph	-6.0 dB	
Resilient Wheels	0 dB		Resilient wheels do not generally affect ground-borne vibration except at frequencies greater than about 80 Hz.
Worn Wheels or Wheels with Flats	+10 dB		Wheel flats or wheels that are unevenly worn can cause high vibration levels. This problem can be prevented with wheel truing and slip-slide detectors to prevent the wheels from sliding on the track.
Worn or Corrugated Track	+10 dB		If both the wheels and the track are worn, only one adjustment should be used. Corrugated track is a common problem, however, it is difficult to predict the conditions that cause corrugations to occur. Rail grinding can remove rail corrugations.
Crossovers and Other Special Trackwork	+10 dB		Wheel impacts at special trackwork with standard frogs will significantly increase vibration levels. The increase will be less at greater distances from the track. Moveable point frogs mitigate this problem.
Floating Slab Trackbed	Select highest one that applies	-15 dB	The reduction achieved with a floating slab trackbed is strongly dependent on the frequency characteristics of the vibration.
Ballast Mats		-10 dB	Actual reduction is strongly dependent on frequency of vibration.
High Resilience Fasteners		-5 dB	Slab track with track fasteners that are very compliant in the vertical direction can reduce vibration at frequencies greater than 40 Hz.
Resiliently Supported Ties		-10 dB	Resiliently supported tie systems in tunnel have been found to provide very effective control of low-frequency vibration.
Type of Track Structure	Relative to at-grade tie & ballast: Aerial/Viaduct structure Open Cut	 -10 dB 0 dB	The general rule is the heavier the structure, the lower the vibration levels. Putting the track in cut may reduce the vibration levels slightly. Rock-based tunnels will shift vibration to a higher frequency.
	Relative to bored tunnel in soil: Station Cut and Cover Rock-Based	 -5 dB -3 dB -15 dB	

Factors Affecting Vibration Path

Path Factor	Adjustment to Propagation Curve			Comment
Geologic Conditions that Promote Efficient Vibration Propagation	Efficient propagation in soil		+10 dB	Refer to the text for guidance on identifying areas where efficient propagation is possible.
	Propagation in rock layer	**Dist.** 50 ft 100 ft 150 ft 200 ft	**Adjust.** +2 dB +4 dB +6 dB +9 dB	The positive adjustment accounts for the lower attenuation of vibration in rock compared to soil. Because it is more difficult to get vibration energy into rock, propagation through rock usually results in lower vibration than propagation through soil.

Table 8-2 continued . . .		
Factors Affecting Vibration Path		
Path Factor	**Adjustment to Propagation Curve**	**Comment**
Coupling to Building Foundation	Wood Frame -5 dB 1-2 Story Commercial -7 dB 2-4 Story Masonry -10 dB Large Masonry on Piles -10 dB Large Masonry on Spread Footings -13 dB Foundation in Rock 0 dB	The general rule is the heavier the building construction, the greater the coupling loss.
Factors Affecting Vibration Receiver		
Receiver Factor	**Adjustment to Propagation Curve**	**Comment**
Floor-to-floor Attenuation	1 to 5 floors above grade: -2 dB/floor 5 to 10 floors above grade: -1 dB/floor	This factor accounts for dispersion and attenuation of the vibration energy as it propagates through a building.
Amplification due to Resonances of Floors, Walls, and Ceilings	+6 dB	The actual amplification will vary greatly depending on the type of construction. The amplification is lower near the wall-floor and wall-ceiling intersections.
Factors Affecting Ground-borne Noise		
Receiver Factor	**Adjustment to Propagation Curve**	**Comment**
Radiated Sound	Peak frequency of ground vibration: Low frequency (<30 Hz): -50 dB Typical (peak 30 to 60 Hz): -35 dB High frequency (>60 Hz): -20 dB	Use these adjustments to estimate the A-weighted sound level given the average vibration velocity level of the room surfaces. See text for guidelines for selecting low-, typical-, or high-frequency characteristics. Use the high-frequency adjustment for subway tunnels in rock or if the dominant frequencies of the vibration spectrum are known to be 60 Hz or greater.

The following guidelines are used to select the appropriate adjustment factors. Note that the adjustments for wheel and rail condition are not cumulative. When more than one adjustment may apply, the general rule is to apply only the largest adjustment. For example, the adjustment for corrugated rail is 10 decibels and the adjustment for flat spots on wheels is 10 decibels. In an area with both, the projected vibration levels should be increased by 10 decibels, not 20 decibels. Similarly, only one of the vibration mitigation treatments is applied.

Factors Affecting Vibration Source

Train Speed: The levels of ground-borne vibration and noise vary approximately at 20 times the logarithm of speed. This relationship means that doubling train speed will increase the vibration levels approximately 6 decibels and halving train speed will reduce the levels by 6 decibels. The adjustments for 75 to 300 mph using a reference speed of 150 mph are given in Table 8-2. The relationship:

$$adjustment\ (VdB) = 20 \times \log\left(\frac{speed}{speed_{ref}}\right)$$

should be used to calculate the adjustments for other speeds.

Trainsets: The levels of ground-borne vibration and noise generated by a train passby depend heavily on the trainset’s suspension system, wheel condition, and wheel type. The vehicle suspension consists of springs and dampers that affect the vibration transmitted to the track support system by the wheel/rail interaction. Generally, stiff springs tend to increase the frequency and amplitude of vibrations. Deteriorated wheel condition also will increase vibration levels. It can be assumed that a high-speed rail system will have wheels in good condition. However, when older vehicles will be used on new track, it may be appropriate to include an adjustment for wheel condition. Wheels with flat spots or corrugations can cause vibration levels that are 10 decibels higher than normal. Resilient wheels will reduce vibration levels at frequencies greater than the effective resonance frequency of the wheel. Because this resonance frequency is relatively high, often greater than 80 Hz, resilient wheels usually have only a marginal effect on ground-borne vibration.

Track System and Support: The type of rail (welded or special trackwork), the track support system, and the condition of the rail all affect the vibration generated by the track system. The base curve (Figure 8-1) assumes welded rail in good condition. Jointed rail causes higher vibration levels than welded rail; however, track on new high-speed rail systems virtually always will be welded. The wheel impacts at special trackwork, especially frogs at crossovers, create much higher vibration forces than normally experienced on tangent track. Because of the higher vibration levels at special trackwork, crossovers often are the principal areas of vibration impact on new systems. Special spring- or movable-point frogs are used as a method of mitigating the vibration impact. These special frogs eliminate the gaps in the running rail.

Modifying the track support system is another method of mitigating vibration impact. Special track support systems such as ballast mats, highly resilient track fasteners, resiliently-supported ties, and floating slabs all have been shown to be effective in reducing vibration levels.
The condition of the running surface of the rails can strongly affect vibration levels. Factors such as corrugations, general wear, or mill scale on new track can cause vibration levels that are 5 to 15 decibels higher than normal. Mill scale usually will wear off after some time in service. However, the track must be ground to remove corrugations or to reduce the roughness from wear.

Track Structure: The weight and size of the track structure affects the vibration radiated by that structure. Vibration levels will generally be lower for heavier track structures. Hence, the vibration levels from a cut-and-cover concrete double-box tunnel can be assumed to be lower than the vibration from a lightweight, concrete-lined bored tunnel. Whether or not the tunnel will be founded in bedrock is another factor affecting the radiated vibration. Bedrock is considered to be hard rock. It is usually appropriate to consider soft siltstone and sandstone to be more similar to soil than hard rock. As seen in Table 8-2, whether the tunnel is founded in soil or rock will make up to a 15 decibel difference in the vibration levels. The vibration from aerial structures is lower than from at-grade track because of the mass of the structure and the extra distance that the vibration must travel before it reaches the receiver.

Factors Affecting Vibration Path

Propagation Characteristics: The General Assessment process requires the selection of one general propagation characteristic. When considering at-grade vibration sources, the selection is between "normal" vibration propagation and "efficient" vibration propagation. Efficient vibration propagation results in vibration levels approximately 10 decibels higher than normal vibration propagation, which more than doubles the potential impact zone for ground-borne vibration. One difficulty in identifying the cause of efficient propagation is in determining geologic conditions or special source conditions (e.g., rail corrugations or wheel flat spots) that could cause higher-than-normal vibration levels.

Although geologic conditions are known to have a significant effect on the vibration levels, it is rarely possible to develop more than a broad-brush understanding of the vibration propagation characteristics for a General Assessment. The conservative approach would be to use the 10-decibel adjustment for efficient propagation to evaluate all potential vibration impact. The problem with this approach is that it tends to overstate greatly the potential for vibration impact. Hence, it is best to review available geological data and any complaint history from existing rail lines and major construction sites near the high-speed rail corridor to identify areas where efficient propagation is possible. If there is any reason to suspect efficient propagation conditions, then a Detailed Analysis during final design should include vibration propagation tests at the areas identified as potentially efficient propagation sites.

Some geologic conditions are repeatedly associated with efficient propagation. Shallow bedrock, less than 30 feet below the surface, is likely to cause efficient propagation. Other factors that can be important are soil type and stiffness. In particular, soils with heavy clay content have sometimes been associated with efficient vibration propagation. Investigation of soil-boring records can be used to estimate depth to bedrock and the presence of problem soil conditions.

Coupling-to-Building Foundation: Since annoyance from ground-borne vibration and noise is an indoor phenomenon, the effects of the building structure and its foundation on the vibration propagation path must also be considered. Wood frame buildings, such as the typical residential structure, are more easily excited by ground-borne vibration than heavier buildings. In contrast, large masonry buildings with spread footings have a low response to ground-borne vibration.

Factors Affecting Vibration Receiver

Type of Building and Receiver Location in Building: Vibration generally reduces in level as it propagates through a building. As indicated in Table 8-2, a 1- to 2-decibel attenuation per floor is usually assumed. Resonances of the building structure, particularly the floors, will tend to counteract this attenuation and will cause some amplification of the vibration. Consequently, for a wood-frame structure, the building-related adjustments nearly cancel out. The adjustments for the first floor assuming a basement are: -5 decibels for the coupling loss; -2 decibels for the propagation from the basement to the first floor; and +6 decibels for the floor amplification. The total adjustment is -1 decibel.

Vibration Radiated as Ground-Borne Noise: The levels of radiated noise can be estimated given the average vibration amplitude of the room surfaces (floors, walls and ceiling) and the total acoustical absorption in the room. The average result is that the numerical value of sound-pressure level is approximately equal to that of the vibration velocity level when the velocity level is referenced to

$1x10^{-6}$ in/sec. However, to estimate the A-weighted sound level from the velocity level, it is necessary to have some information about the frequency spectrum. The A-weighting adjustment drops rapidly at low frequencies, reflecting the relative insensitivity of human hearing to low frequencies. For example, A-weighting is -16 dB at 125 Hz, -26 dB at 60 Hz and -40 dB at 30 Hz. Adjustments for vibration depending on whether it has low-frequency, typical or high-frequency characteristics are provided in Table 8-2. Some general guidelines for classifying the frequency characteristics are:

- Low Frequency: Low-frequency vibration characteristics can be assumed for most surface track, tunnels surrounded by sandy soil with low cohesion, or a track support system with vibration isolation.
- Typical: The typical vibration characteristic is the default assumption to be used for tunnels unless information indicates that one of the other assumptions is appropriate. It should be used for surface track when the soil is very stiff with a high clay content.
- High Frequency: High-frequency characteristics should be assumed for tunnels whenever the transit structure is founded in rock or when there is very stiff clay soil.

A factor that can be particularly complex to address is the effect of vibration propagation through rock. There are three factors from Table 8-2 that need to be included when a tunnel will be founded in rock:

- The -15 decibel adjustment in the "Type of Track Structure" category.
- The adjustment based on the propagation distance in the "Geologic Conditions" category. This positive adjustment increases with distance because vibration attenuates more slowly in rock than in soil.
- The "Coupling to Building" category. When a building foundation is directly on the rock layer, there is no "coupling loss" due to the weight and stiffness of the building. The standard coupling factors should be used if there is at least a 8-foot layer of soil between the building foundation and the rock layer.

8.3 INVENTORY OF VIBRATION IMPACT

The results of the General Assessment are expressed in terms of an inventory of all sensitive land uses where either ground-borne vibration or ground-borne noise from the project exceed the impact thresholds described in Chapter 7. The General Assessment may include a discussion of mitigation measures likely be needed to reduce vibration to acceptable levels at impacted locations.

The purpose of the General Assessment procedure is to develop a reasonably complete inventory of the buildings that may experience ground-borne vibration or ground-borne noise that exceed the impact criteria. At this point, a conservative assessment of the impact is preferred. It is better to include some buildings where ground-borne vibration may be below the impact threshold than to exclude buildings where it may exceed the impact threshold.

The steps for developing the inventory are:

Step 1: Identification of Vibration-sensitive Land Uses

1) Identify all vibration-sensitive land uses within Screening Distance from Table 8-1.
2) Categorize vibration-sensitive land uses according to the categories in Table 7-1.
3) Construct tables of land uses by category.

Step 2: Estimation of Vibration Impact

1) Apply General Assessment procedure to obtain ground-borne vibration and ground-borne noise levels at each sensitive land use identified in Step 1.
2) Compare estimation with impact thresholds in Table 7-1.
3) Identify vibration-sensitive land uses where impact thresholds are exceeded.

Step 3: Preparation of Impact Inventory

1) Prepare summary tables showing the number of buildings in each category impacted by ground-borne vibration and ground-borne noise. This tabluation is done for each alternative.
2) Utilize the summary tables to compare alternatives by the number of buildings impacted.

Step 4: Mitigation of Impact

1) Select appropriate mitigation method from Section 9-4.
2) Re-assess impacts based on application of mitigation measures.

An example of a receiver-specific General Vibration Assessment for a hypothetical high-speed rail project follows. The assumed parameters of the project and receiver are typical of the preliminary planning stage of a project, and it is assumed that no project-specific vibration measurements have been performed.

Example 8-1. General Vibration Assessment of a High-Speed Train Alignment

A high-speed train proposed for a corridor in the Midwest passes through a suburb an average of once an hour. A hospital is located 30 feet from the right-of-way line. The train speed is projected to be 120 mph in this section. The tracks are continuously welded on concrete tie-and-ballast in this at-grade section. The distance from track centerline to the right-of-way is 50 feet. Soil conditions are unknown. Determine if ground-borne vibration and noise from the train will cause impact on the second floor of this three-story brick building.

Step 1: Identification of Vibration-Sensitive Land Use

1) **Category** . A hospital is categorized in "Vibration Category 2: Residential" according to Chapter 7.

2) **Screen**. The "Vibration Screening Procedure" in Section 8.1 shows that for a 120-mph train with "infrequent" service (less than 70 passbys per day), a residential land use within 100 feet should be identified as a potentially affected location. The hospital is located 80 feet from the tracks, well within the screen distance.

Step 2: Estimation of Vibration Impact

1) **Base Curve**. The "Generalized Ground-Borne Vibration Curve" (Figure 8-1) shows a vibration level of 78 VdB at 80 feet for a train at 150 mph.

2) **Adjustments**. Refer to Table 8-2.

2.1 *Speed Adjustment*. Adjustments for speeds other than 150 mph are included in Table 8-2. Unfortunately, 120 mph is not one of the adjustments given. Therefore, the speed correction of 20 log (speed/150) is used.

$$20 \log (120/150) = -1.9 \text{ dB}$$

Round off to -2 dB.

2.2 *Trainsets*. Assume wheels in good condition. No adjustment is applied.

2.3 *Track System*. Assume rails are in good condition. No adjustment.

2.4 *Track Structure*. At-grade tie and ballast is the reference condition. No adjustment is applied.

2.5 *Propagation Characteristics*. Propagation is considered to be normal unless proven otherwise. The soil conditions are unknown, so assume no adjustment.

2.6 *Type of Building and Receiver Location*. The hospital building falls into the category of "2-4 Story Masonry" so the coupling adjustment is -10db. The receiver is on the 2nd floor so the "Floor-to-floor Attenuation" is -2dB. Low-frequency characteristics can be assumed for most surface track, so the "Radiated Sound" adjustment is -50dB to convert the vibration level in VdB to sound level in dBA.

2.7 *Calculation*

i. Ground-Borne Vibration:

Base vibration level	=	78 VdB
Speed adjustment	=	-2 dB
Wheel condition	=	0 dB

```
Track system           =   0 dB
Track structure        =   0 dB
Propagation            =   0 dB
Foundation coupling    = -10 dB
Receiver location      =  -2 dB
Floor response         =  +6 dB
                         _______
Estimated Vibration
          Level        =  70 VdB
```

ii. Ground-Borne Noise:

```
Vibration Level        =  70 VdB
Radiated Sound         = -50 VdB to dBA adjustment
                         ________
Estimated Sound Level  =  20 dBA
```

2.8 *Impact Assessment*. Ground-borne vibration and noise impact criteria are given in Table 7-1. The hospital in this case falls under "Category 2: Residential" land uses exposed to "Infrequent Events." The corresponding threshold for ground-borne vibration impact is 80 VdB and for ground-borne noise impact is 43dBA. Neither threshold is exceeded at the hospital.

End of Example 8-1

Chapter 9

DETAILED VIBRATION ASSESSMENT

The Detailed Assessment approach presented in this chapter provides a means to determine general vibration propagation conditions along a proposed high-speed rail corridor and to develop specific projections for sensitive buildings where vibration impact is predicted by a General Assessment. The goal of the Detailed Assessment is to develop accurate projections of ground-borne vibration using all available tools and, when necessary, to design mitigation measures.

Local geologic conditions can have a very large effect on the impact distances of ground-borne vibration. This effect was dramatically demonstrated by the vibration test results described in Chapter 6. Vibration measurements of the X2000 trains in Sweden indicate that, at the test site, impacts could occur at distances greater than 300 feet from the tracks. In contrast, the tests also showed that the X2000 trains at the TGV test site in France would not cause vibration impacts beyond about 60 feet. The difference appears to be entirely due to the geologic conditions.

Projections using the General Assessment procedures described in Chapter 8 are based on the high range of data from sites that appear to have "normal" geology. This means that the actual levels of ground-borne vibration will usually be 5 VdB or more lower than projections developed using the General Assessment curve and adjustments, and will rarely exceed projections developed using the General Assessment approach. However, an important qualification is that there will be some, apparently rare, conditions where the actual levels of ground-borne vibration will be substantially higher than those projected using the General Assessment procedures.

As indicated above, it can be appropriate to use the Detailed Assessment procedures at several locations along the proposed corridor during the preliminary phases of a high-speed rail project to refine the General Assessment projection curves. A Detailed Assessment is also appropriate during the final design and engineering phases for areas where a General Assessment has indicated the potential for impact.

Procedures for developing detailed assessments of ground-borne vibration are constantly evolving. Analytical techniques for solving vibration problems are complex and the technology continually advances. The material contained in this chapter is not intended to provide the novice with a complete methodology for conducting a Detailed Assessment. Rather, the approach presented focuses on the key steps usually taken by a qualified professional.

Three examples of cases where Detailed Vibration Assessment might be required are:

1. *A particularly sensitive building, such as a major concert hall, is within the impact zone. A Detailed Assessment would ensure that effective vibration mitigation is feasible and economically reasonable.*

2. *The General Assessment indicates that a proposed high-speed rail project may create vibration impact for a large number of residential buildings adjacent to the alignment. The projections for many of the buildings exceed the impact threshold by less than 5 decibels, which means that more accurate projections may show that vibration levels will be below the impact criterion. If the cost of measures to mitigate vibration would significantly increase project costs, a Detailed Assessment to determine the vibration impact as accurately as possible is warranted.*

3. *A high-speed rail alignment will be close to university research buildings where vibration-sensitive optical instrumentation is used. Vibration from the trains could make it impossible to continue to use the building for this type of research. A Detailed Assessment would determine if it is possible to control the vibration from the trains so that sensitive instrumentation would not be affected.*

A Detailed Vibration Assessment consists of three main steps:

Step 1. Survey Existing Vibration. Although knowledge of the existing levels of ground-borne vibration is not usually required for the assessment of vibration impact, a survey of the existing vibration may be valuable in some instances. Examples include documenting existing background vibration at sensitive buildings, measuring the vibration levels created by sources such as existing rail lines, and, in some cases, characterizing the general background vibration in the project corridor. Characterizing existing vibration conditions is discussed in Section 9.1.

Step 2. Predict Future Vibration and Vibration Impact. All of the available analytical tools should be applied in a Detailed Assessment to develop the best possible estimates of the potential for vibration impact. An approach to projecting ground-borne vibration that consists of measuring vibration propagation characteristics at specific sites is discussed in Section 9.3. The vibration propagation test procedure is described in Section 9.3 and the assessment of vibration impact is discussed in Section 9.1.

Step 3. Develop Mitigation Measures. Controlling the impact from ground-borne vibration requires developing cost-effective measures to reduce the vibration levels. The Detailed Assessment can identify practical vibration control measures that will be effective at the dominant vibration frequencies and compatible with the given trackway structure (aerial, at-grade, subway) and track support system. Vibration mitigation measures are discussed in Section 9.4.

The discussion in this chapter generally assumes vibration analysis of steel-wheel rail systems. The procedures are equally applicable to maglev systems; however, because all available data indicate low levels of ground-borne vibration generated by maglev trains, analysis of ground-borne vibration for a proposed maglev system is generally unnecessary.

9.1 ASSESSMENT OF VIBRATION IMPACT

The purposes of the vibration impact assessment are to inventory all sensitive land uses that may be adversely affected by the ground-borne vibration and noise from a proposed high-speed rail project and to determine the mitigation measures that will be required to eliminate or minimize the impacts. This requires projecting the levels of ground-borne vibration and noise, comparing the projections with the appropriate impact criteria, and developing a list of suitable mitigation measures. The General Assessment is incorporated as an intermediate step in the impact assessment because of its relative simplicity and potential to narrow the areas requiring Detailed Assessment.

The assessment of vibration impact proceeds according to the following steps:

Step 1: Screening. Screen the entire proposed high-speed rail corridor to identify areas where there is the potential for impact from ground-borne vibration. The vibration screening method is described in Chapter 8. If sensitive land uses are not located within the screening distances, it is not necessary to perform any further assessment of ground-borne vibration.

Step 2: Vibration Source Levels. Define a curve of ground-surface vibration level as a function of distance that can be used with the General Assessment. Usually this will mean selecting the generalized curve from Figure 8-1 or adapting measurements from an existing facility.

Step 3: Vibration Propagation Characteristics. Use the General Assessment Procedure to estimate vibration levels for specific buildings or groups of buildings.

Step 4: Study Area Characteristics. In some cases a vibration survey to characterize existing ambient vibration may be necessary. As discussed in Section 9.2, although knowledge of the existing ambient vibration is not generally required to evaluate vibration impact, there are times when a survey of existing conditions is valuable. One common example is when the rail project will be located in an existing rail right-of-way shared by freight trains. Guidelines on the procedure to be used to account for existing vibration that is higher than the impact limit for the project vibration are provided in Chapter 7.

Step 5: Vibration Impact Estimation and Inventory. Compare the projected levels with the impact criteria given in Table 7-1 to determine whether vibration impact is likely. The goal of this step is to develop a reasonably accurate catalog of the buildings that will experience ground-borne vibration or noise levels that exceed the criteria. In the General Assessment, it is best to make a conservative assessment of the impact by including some buildings where the actual vibration ultimately is at or slightly below the impact threshold. Usually it is far easier to control vibration during design and construction rather than to retrofit vibration control measures to solve unanticipated problems that develop once the system is operational. In locations where General Assessment indicates impact, the more refined techniques of Detailed Assessment should be employed.

Step 6: Vibration Mitigation. For areas where the impact criteria may be exceeded, review potential mitigation measures and assemble a list of feasible approaches to vibration control. To be feasible, the measure, or combination of measures, must be capable of providing a significant reduction of the vibration levels, usually at least 4 dB, while being cost effective.

Because vibration control is frequency-dependent, specific recommendations of vibration control measures can be made only after the frequency characteristics of the vibration have been evaluated. Use the Detailed Vibration Assessment to develop specific mitigation recommendations where it is important to estimate the spectrum of ground-borne vibration at potentially affected buildings. This type of assessment is often performed during final design rather than during the environmental assessment stage. Because a Detailed Assessment is more accurate than a General Assessment, there will be cases where the Detailed Assessment will show that the vibration and noise levels will be below the applicable criteria and that mitigation is not required. If the projected levels are still above the limits, the spectra provided by the Detailed Assessment should be used to evaluate mitigation measures.

9.2 CHARACTERIZING EXISTING VIBRATION CONDITIONS

Ambient vibration is rarely of sufficient magnitude to be perceptible or to cause audible ground-borne noise unless there is a specific vibration source close by, such as a rail line. In most cases, perceptible vibration inside a building is caused by equipment or activities within the building itself, such as heating and ventilation systems, footsteps, or doors closing. Because the existing ambient vibration is usually below human perception, a limited survey is sufficient even for a Detailed Assessment. This contrasts with analysis of noise impact, where documenting the existing ambient noise level is required to assess the impact.

Examples of situations where measurements of the ambient vibration are valuable include:

- **Determining existing vibration at sensitive buildings.** Serious vibration impact may occur when there is vibration-sensitive manufacturing, research, or laboratory activities within the screening distances. Careful documentation of the existing vibration will provide valuable information on the real sensitivity of the activity to external vibration and will provide a reference condition under which vibration is not a problem.

- **Using existing vibration sources to characterize propagation.** Existing vibration sources such as freight trains, industrial processes, quarrying operations, or normal traffic sometimes can be used to characterize vibration propagation. Carefully designed and performed measurements may eliminate the need for more complex propagation tests.
- **Documenting existing levels of general background vibration.** Some measurements of the existing levels of background vibration can be useful simply to document that, as expected, the vibration is below the normal threshold of human perception. Existing vibration in urban and suburban areas is usually due to traffic. If a measurement site has existing vibration approaching the range of human perception (e.g., the maximum vibration velocity levels are greater than about 65 VdB), then this site should be carefully evaluated for the possibility of ground conditions causing "efficient" vibration propagation. Areas with efficient vibration propagation could have vibration problems when the project is built.
- **Documenting vibration from existing rail lines.** Measurements to document the levels of vibration created by existing rail lines can be important in evaluating the impact of the new vibration source and determining vibration propagation characteristics in the area. As discussed in Chapter 7, if vibration from an existing rail line will be higher than that from the high-speed rail trains, there may not be impact even though the normal impact criterion would be exceeded.

Although ground-borne vibration is almost exclusively a problem inside buildings, measurements of existing ambient vibration generally should be performed outdoors. Two important reasons for this are: (1) equipment inside the building may cause more vibration than exterior sources, and (2) the building structure and the resonances of the building can have strong, but difficult to predict, effects on the vibration. However, there are situations where measurements of indoor vibration are appropriate. For example, documenting vibration levels inside a vibration-sensitive building can be important since equipment and activities inside the building may cause vibration greater than that from external sources such as street traffic or aircraft overflights. Floor vibration measurements are taken near the center of a floor span where the vibration amplitudes are the highest.

The goal of most ambient vibration tests is to characterize the root mean square (RMS) vertical vibration velocity level at the ground surface. In almost all cases, it is sufficient to measure only vertical vibration and ignore the transverse components of the vibration. Although transverse components can transmit significant vibration energy into a building, the vertical component usually has greater amplitudes than transverse vibration. Moreover, vertical vibration is usually transmitted more efficiently into building foundations than transverse vibration.

The manner in which a transducer used to measure vibration is mounted can affect the measured levels of ground-borne vibration. However, research has shown that, at the frequencies usually of concern for ground-borne vibration (generally less than 200 Hz), straightforward methods of mounting transducers on the ground surface or on pavement are adequate for vertical vibration measurements.[1,2,3] Quick-drying epoxy or beeswax can be used to mount transducers to smooth paved surfaces or to metal stakes driven into the ground. Rough concrete or rock surfaces require special mountings. One approach is to use a liberal base of epoxy to attach small aluminum blocks to the surface and then mount the transducers on the aluminum blocks.

Selecting sites for an ambient vibration survey primarily requires good common sense. Sites selected to characterize a high-speed rail corridor should be distributed along the entire project and should be representative of the types of vibration environments found in the corridor. These would commonly include:

- sites in quiet residential areas removed from major traffic arterials to characterize low-ambient vibrations,
- sites along major traffic arterials and highways or freeways to characterize high vibration areas,
- sites in any area with vibration-sensitive activities, and
- sites near any significant existing source of vibration such as a railroad line.

The transducers should be located near the building setback line for background vibration measurements. Ambient measurements along railroad lines ideally will include: multiple sites; several distances from the rail line at each site; and 4 to 10 train passbys for each test. Because of the irregular schedule for freight trains and, on many rail lines, the low number of operations each day, it is often impractical to perform tests at more than two or three sites along the rail line or to measure more than two or three passbys at each site. Rail type and condition strongly affect the vibration levels. Consequently, the track at each measurement site should be inspected by experienced personnel to locate any switches, bad rail joints, corrugations, or other factors that could be responsible for higher than normal vibration levels.

The appropriate methods of characterizing ambient vibration are dependent on the type of information required for the analysis. Some examples are as follows:

Ambient Vibration: Ambient vibration is usually characterized with a continuous 10- to 30-minute measurement of vibration. The equivalent energy level, or L_{eq}, of the vibration velocity level over the measurement period gives an indication of the average vibration energy. L_{eq} is equivalent to a

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[1] J.T. Nelson, H.J. Saurenman, G.P. Wilson, "Metrorail Operational Sound Level Measurements: Ground-Borne Vibration and Noise Levels," prepared by Wilson Ihrig & Associates for Washington Metropolitan Area Transit Authority, December 1979.

[2] T.G. Gutowski, L.E. Wittig, C.L. Dym, "Some Aspects of the Ground Vibration Problem," *Noise Control Engineering*, vol. 10:3, pp 94-101, 1978.

[3] H. Nolle, "High Frequency Ground Vibration Measurements," *Shock and Vibration Bulletin*, vol. 48:4, pp 95-103, 1978.

long averaging time RMS level. Specific events can be characterized by the maximum RMS level (L_{max}) of the event or by performing a statistical analysis of RMS levels over the measurement period. An RMS averaging time of one second should be used for statistical analysis of the vibration level.

Specific Events: Specific events such as train passbys should be characterized by the RMS level during the time that the train passes by. If the locomotives have vibration levels more than 5 VdB higher than the vehicles, a separate RMS level for the locomotives should be obtained. The locomotives usually can be characterized by the L_{max} during the train passby. The RMS averaging time or time constant should be one second when determining L_{max}. Sometimes it is adequate to use L_{max} to characterize the train passby, which is simpler to obtain than the RMS averaged over the entire train passby.

Frequency Analysis: When the vibration data will be used to characterize vibration propagation or for other special analysis, a frequency analysis of the vibration is required. An example would be if vibration transmission characteristics of the ground are suspected of having particular frequency characteristics. For many analyses, 1/3 octave band charts are best for describing the vibration characteristics. Narrowband spectra also can be valuable, particularly for identifying pure-tone characteristics and designing mitigation measures.

It is preferable that ambient vibration be characterized in terms of the RMS velocity level, not the peak particle velocity (PPV), which is commonly used to monitor construction vibration. As discussed in Chapter 6, RMS velocity level is considered to be better correlated to human response than PPV.

9.3 VIBRATION PREDICTION PROCEDURE

9.3.1 Background

Predicting ground-borne vibration associated with a transportation project is a developing field. Because ground-borne vibration is a complex phenomenon that is difficult to model and predict accurately, most projection procedures that have been used for high-speed rail and other types of rail projects rely on empirical data. Although no single method stands out as the best approach for all situations, the procedure described in this section is one of the most promising because it is based on site-specific tests of vibration propagation. The procedure, which was developed under an FTA (formerly UMTA) research contract,[4] is recommended for detailed evaluations of ground-borne vibration. The same procedure is discussed in Chapter 11 of the FTA manual *Transit Noise and Vibration Impact*

[4] J.T. Nelson, H.J. Saurenman, "A Prediction Procedure for Rail Transportation Ground-Borne Noise and Vibration," Transportation Research Record 1143, National Research Council, Transportation Research Board (Washington, D.C.), August 1988.

Assessment.[5] Other approaches to predicting ground-borne vibration have included pure analytical and pure numerical approaches. Some of these approaches were presented at an international workshop on railway noise.[6]

There is still work to be done before a comprehensive prediction method will be available that can be confidently applied on sensitive projects. The measurements of high-speed rail vibration performed in France, Italy, and Sweden as part of preparation of this manual are discussed in Chapter 6. An important observation from those tests is that vibration from high-speed trains is not caused by mechanisms that are substantially different than vibration from lower speed trains such as rapid transit and light rail trains. This means that procedures for predicting vibration from transit and passenger trains are equally applicable to high-speed trains, following scaling to the appropriate speed. The data show that vibration amplitudes are approximately proportional to $20 \times log(\text{speed})$ from 50 mph to over 150 mph.

Perhaps the biggest problem for most prediction approaches is that vibration propagation through the soil and rock layers that are between the source and the receiver is extremely difficult to define. Attenuation along the propagation path is a critical component of any prediction procedure. Even when boreholes are made at regular intervals along a rail alignment, unless the geology is very uniform, they do not uncover geologic variations along the vibration propagation path from the rail line to receiver, which is perpendicular to the tracks. A primary goal of the procedure presented in this section is to characterize vibration propagation with empirical tests. This makes it unnecessary to infer propagation characteristics from standard geologic parameters such as soil classification, wave speed, and density. Experience has shown that the test procedure provides a reasonable estimate of vibration propagation characteristics and that it can identify areas where ground-borne vibration will be higher than normal because of geologic conditions that promote efficient propagation.

9.3.2 Overview of Prediction Procedure using Measured Transfer Mobility

The prediction method described in this section was developed to enable train vibration measurements collected in one city to be used to predict vibration levels in another city where the geologic conditions may be completely different. The procedure uses a special measured function, called *transfer mobility*, which defines the relationship between an exciting force and the resulting vibration velocity at the ground surface. The transfer mobility combines the effects of the media the vibration waves pass through, the types of vibration waves, and all possible paths the vibration can take to go from the source to the receiver.

Transfer mobility is a function of both frequency and distance from the source. The transfer mobility between two points completely defines the composite vibration propagation characteristics between the two points. In most practical cases, receivers are close enough to the train tracks that the vibration

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[5] U.S. Department of Transportation, Federal Transit Administration, *Transit Noise and Vibration Impact Assessment*, Report DOT-T-95-16, April 1995.

[6] "The Fifth International Workshop on Railway and Tracked Transit System Noise," Voss, Norway, June 21-24, 1995, (Proceedings published in *Journal of Sound Vibration*, Vol. 193, No. 1, 1996).

cannot be considered to be originating from a single point; the vibration source is more appropriately characterized as a line source. Consequently, the point transfer mobility must be modified to approximate a line source. In the text that follows, TM_{point} is used to indicate the measured point source transfer mobility and TM_{line} is used for the line source transfer mobility derived from TM_{point}. Both are assumed to be in decibels with consistent reference quantities.

Predicting ground-borne vibration at a specific site requires the transfer mobility function for the site and an applicable force density function. The force density function is usually derived from measurements at an existing high-speed rail line. In essence, the force density is the normalized ground-borne vibration with the effects of geology removed. The measured transfer mobility of a site along an existing high-speed rail system can be used to estimate the force density function that is independent of the geology.

The prediction procedure considers ground-borne vibration to be divided into the following components:

1. **Excitation Force (Force Density):** The vibration energy is created by oscillatory and impulsive forces. Steel wheels rolling on smooth steel rails create random oscillatory forces. When a wheel encounters a discontinuity such as a rail joint, an impulsive force is created. The force excites the track structure, such as the railway tunnel, or the ballast for at-grade track. In the prediction method, the combination of the actual force generated at the wheel/rail interface and the vibration of the track structure are usually combined into an equivalent force density level. The force density level describes the force that excites the soil/rock surrounding the track structure.
2. **Vibration Propagation (Transfer Mobility):** The excitation of the track structure causes vibration waves in the soil that propagate away from the track structure. Vibration energy can propagate through the soil or rock in a variety of wave forms. All ground vibration includes shear and compression waves. In addition, Rayleigh waves, which propagate along the ground surface, can be a major carrier of vibration energy. The mathematical modeling of vibration is complicated when, as is usually the case, there are soil strata with different elastic properties. The propagation through the soil/rock is modeled using the experimentally determined transfer mobility.
3. **Building Vibration:** When the ground vibration excites a building foundation, it sets the building into motion and starts vibration waves propagating throughout the building structure. The interaction between the ground and the foundation causes some reduction in vibration levels. The amount of reduction depends on the mass and stiffness of the foundation. The more massive the foundation, the lower the response to ground vibration. As the vibration waves propagate through the building, they can create perceptible vibration and cause annoying rattling of windows and decorative items either hanging on walls or located on shelves.
4. **Audible Noise:** In addition to perceptible vibration, the vibration of room surfaces radiates low-frequency sound that may be audible. The sound level is affected by the amount of acoustical absorption in the receiver room.

The combination of the force density level and the transfer mobility is used to predict the ground-surface vibration. A fundamental assumption of the prediction approach outlined here is that the force density, transfer mobility, and the building coupling to the ground are all independent factors. The following equations are the basis for the prediction procedure, where all of the quantities are in decibels with consistent reference values:

$$L_v = L_F + TM_{line} + C_{build}$$

$$L_A = L_v + K_{rad} + K_{A\text{-}wt}$$

where:

- L_v = RMS vibration velocity level in one 1/3 octave band,
- L_A = A-weighted sound level in one 1/3 octave band,
- L_F = force density for a line vibration source such as a train,
- TM_{line} = line source transfer mobility from the tracks to the sensitive site,
- C_{build} = adjustments to account for ground–building foundation interaction and attenuation of vibration amplitudes as vibration propagates through buildings,
- K_{rad} = adjustment to convert from vibration to sound pressure level, which also for the amount of acoustical absorption inside the room (A value of zero can be used for K_{rad} for typical residential rooms when the decibel reference value for L_v is 1 micro in./sec.[ref. 4]), and
- $K_{A\text{-}wt}$ = A-weighting adjustment at the 1/3 octave band center frequency.

All of the quantities given above are functions of frequency. The standard approach to dealing with the frequency dependence is to develop projections on a 1/3 octave band basis using the average values for each 1/3 octave band. The end result of the analysis is the 1/3 octave band spectra of the ground-borne vibration and the ground-borne noise. The spectra are then used to calculate overall vibration velocity level and the A-weighted sound level. This is in contrast to the General Assessment procedures, where the overall vibration velocity level and A-weighted sound level are predicted without any consideration of the particular frequency characteristics of the propagation path.

9.3.3 Measuring Transfer Mobility and Force Density (Vibration Propagation Testing)

The overall purpose of vibration propagation testing is to obtain data that can be used to estimate the following quantities:

1. Point Source Transfer Mobility. This is basically an intermediate quantity that is applicable to point vibration sources. It is a function of both frequency and distance from the source.

2. Line Source Transfer Mobility. The measured point source transfer mobilities are used to estimate an equivalent line source transfer mobility for each test site.

3. Force Density. The force density characterizes the vibration-generating characteristics of the train/track system that will be used. It can be based on previous measurements, or testing can be done at an existing facility to measure the force density. If no suitable measurements are available, testing should be done at a high-speed rail facility with equipment similar to the planned vehicles. Adjustments for factors such as train speed, track support system, and vehicle suspension will